EBIS

Jim Alessi

- Basic idea
- Test stand results
- RHIC EBIS
- RFQ, Linac, Matching
- Where it would go

People who have "helped" (i.e., done all the work!)

- Ed Beebe, Sasha Pikin, Ahovi Kponou
- Krsto Prelec, Ady Hershcovitch, Deepak Raparia

- John Ritter, Lou Snydstrup, Steve Bellavia
- Dave Graham, Bob Lockey, Omar Gould

- Dan McCafferty, Bob Schoepfer, Dave Cattaneo
- Dave Boeje, Tim Lehn

- Andy McNerney

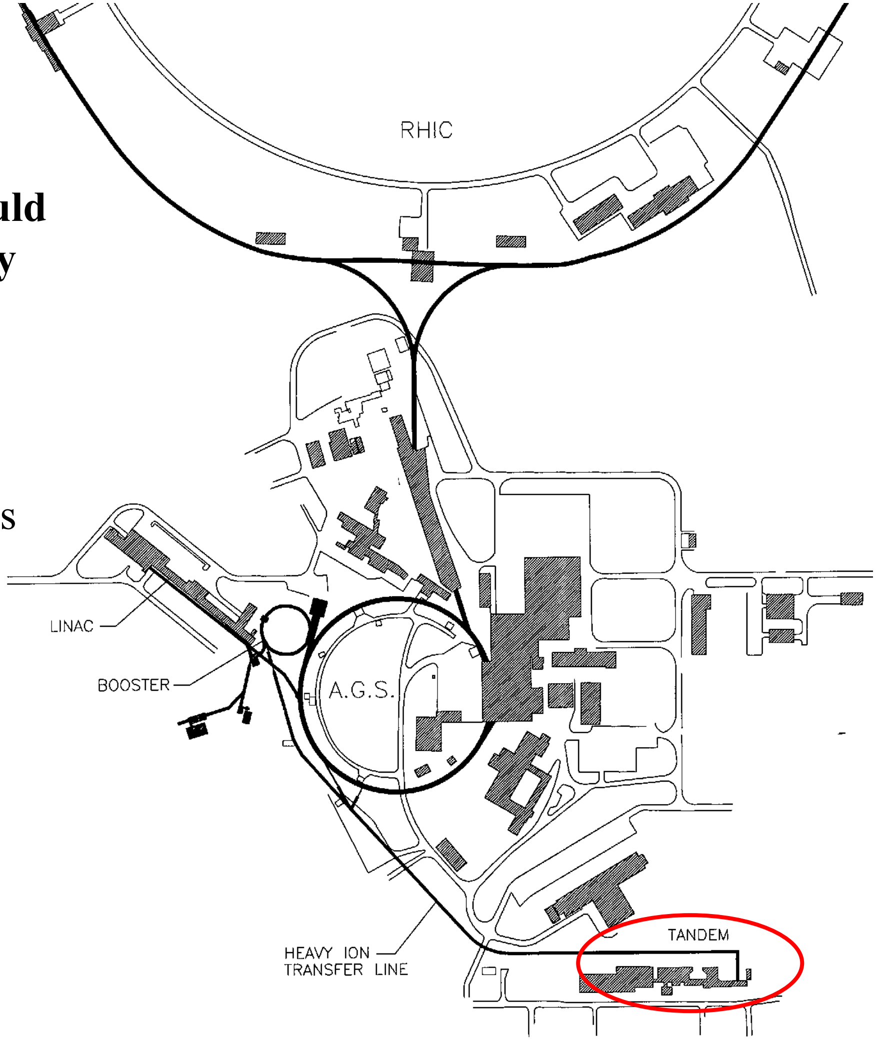
- Collaborations: Budker Institute; Mann Siegbahn Institute

(Note: support is not quite as extensive as this list makes it look.)

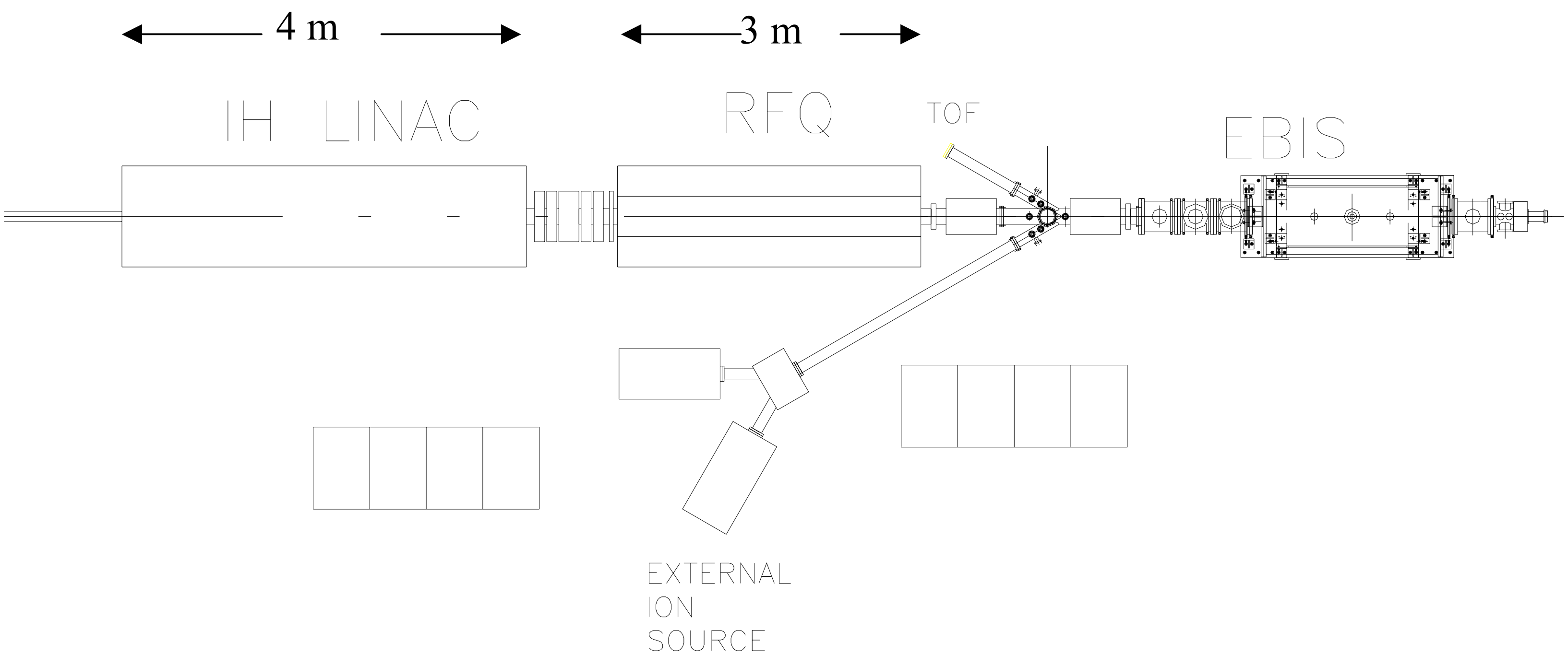
Heavy Ion Preinjector for RHIC

The Tandem Van de Graaff is the present RHIC preinjector. Until our recent EBIS development, it was the only option which could meet RHIC requirements, and while presently it is quite reliable, it has disadvantages -

- 860 m transport line to Booster
- Stripping foils at terminal and high energy lead to intensity & energy spread variations
- Injection over > 40 turns is required
- Limitations on ion species (must start with negative ions)
- High maintenance, manpower
- Obsolete equipment requires upgrading

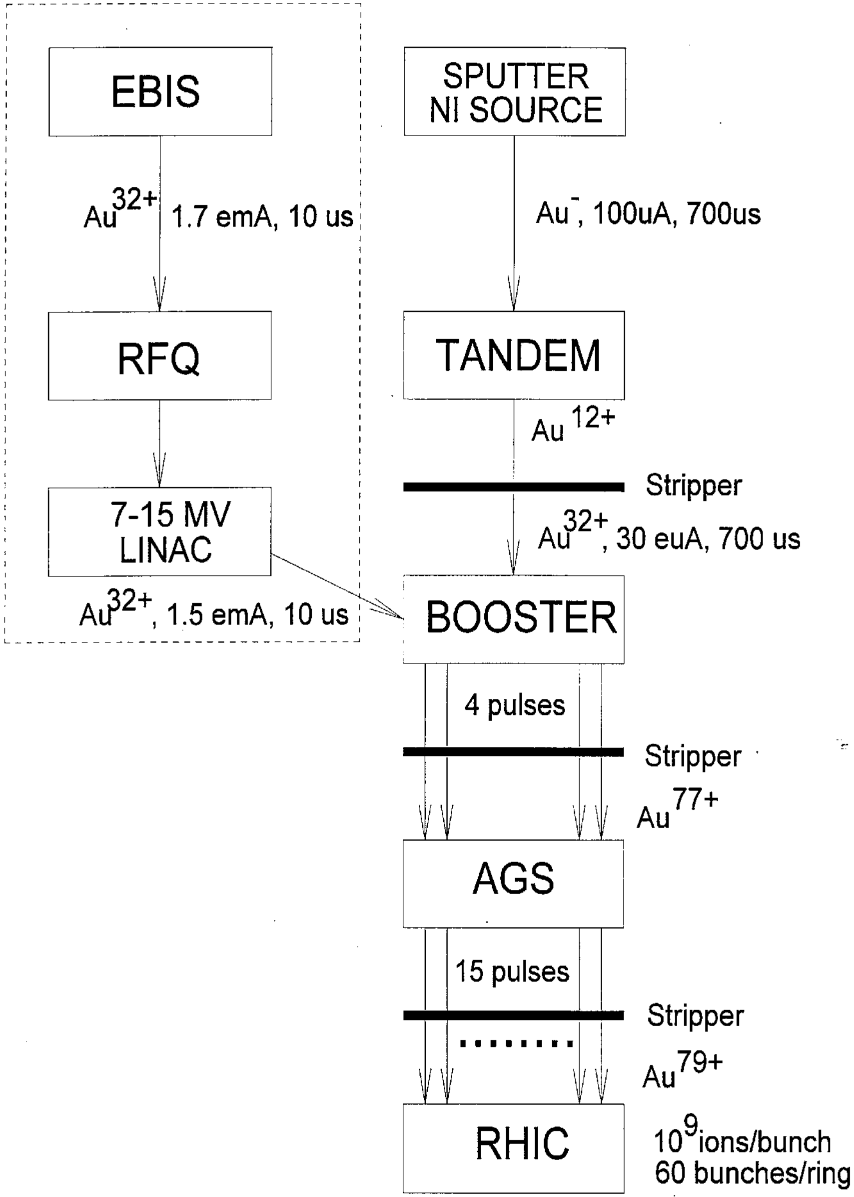


Proposed Linac –Based RHIC Preinjector



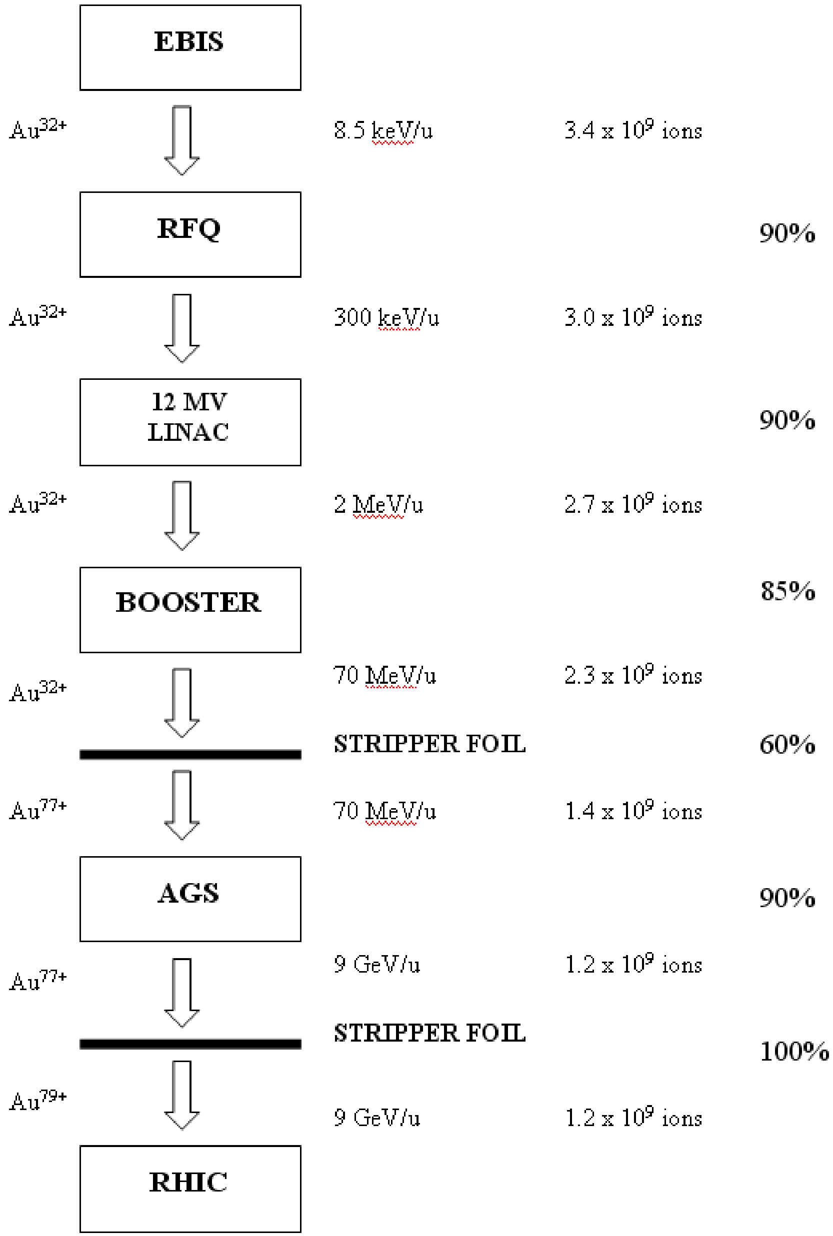
RFQ: 8.5 - 300 keV/u; 100 MHz

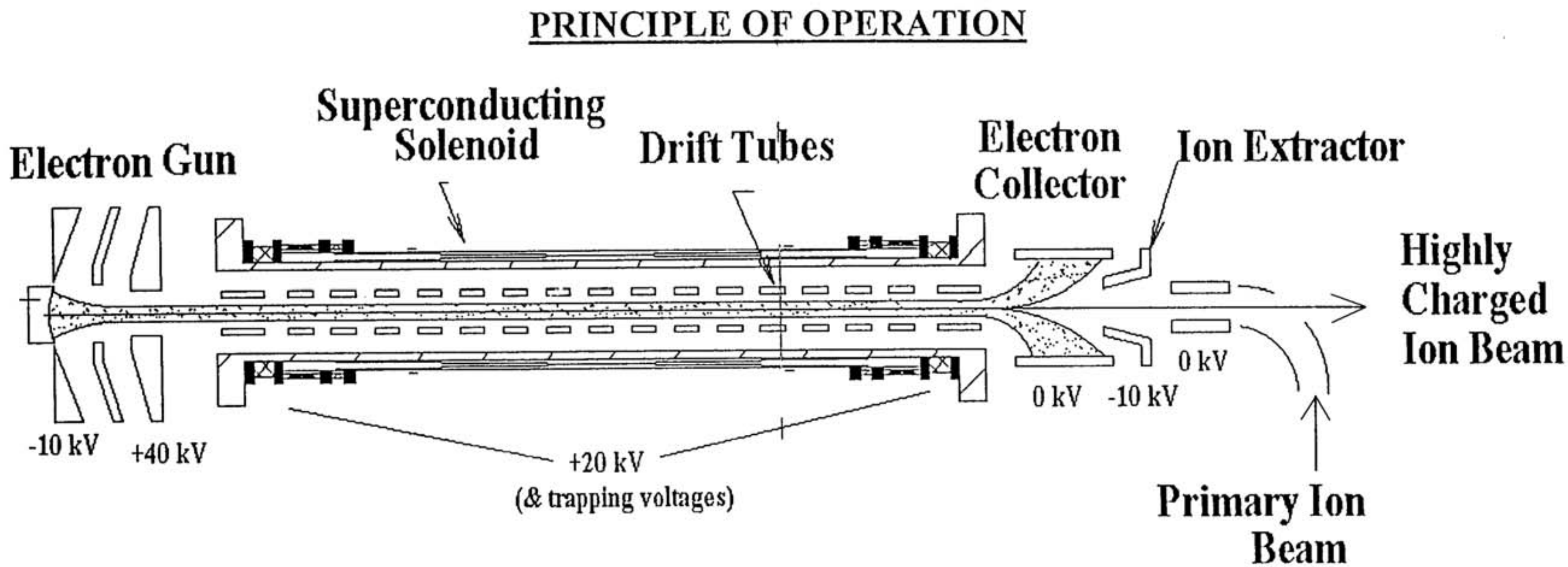
Linac: 0.3 - 2.0 MeV/u; 100 MHz



Advantages of the new preinjector:

- Simple, modern, low maintenance
- Lower operating cost
- Can produce any ions (U, $He^3\uparrow$)
- Higher Au injection energy into Booster
- Fast switching between species
- Short transfer line to Booster (30 m)
- Few-turn injection
- No stripping needed before the Booster
- Expect future improvements to lead to higher intensities


EBIS
Au32+
8.5 keV/u
3.4 x 10^9 ions
RFQ
90%
Au32+
300 keV/u
3.0 x 10^9 ions
12 MV LINAC
90%
Au32+
2 MeV/u
2.7 x 10^9 ions
BOOSTER
85%
Au32+
70 MeV/u
2.3 x 10^9 ions
STRIPPER FOIL
60%
Au77+
70 MeV/u
1.4 x 10^9 ions
AGS
90%
Au77+
9 GeV/u
1.2 x 10^9 ions
STRIPPER FOIL
100%
Au79+
9 GeV/u
1.2 x 10^9 ions
RHIC



Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrode electrostatic potentials.

Ion output per pulse is proportional to the trap length and electron current.
Ion charge state increases with increasing confinement time.

<u>Attractive features of an EBIS</u> (compared to ECR, LIS)

- **One has control over pulse width, extracting a fixed charge – a good match to synchrotron requirements**

- **EBIS produces a narrow charge state distribution (20% in the desired charge state), so there is less of a space charge problem in the extraction and transport of the total current**

- **One has control over the charge state produced (easy to get intermediate charge states, such as Au^{32+} or U^{45+})**

- **An EBIS can produce any type ions – from gas, metals, etc., and is easy to switch species**

- **The scaling laws are understood**

- **The source is reliable, and has excellent pulse-to-pulse stability, long life**

Linac-based Preinjector - Source “requirements”

1. Intensity for 1 x 10^9 Au ions/bunch in RHIC : ~ 3 x 10^9 Au^{32+} ions/pulse from the source

2. No stripping before Booster injection : $q/m > 0.16$ (Au^{32+}, Si^{14+}, Fe^{21+})

3. 1-4 turn injection into Booster : pulse width 10-40 μs

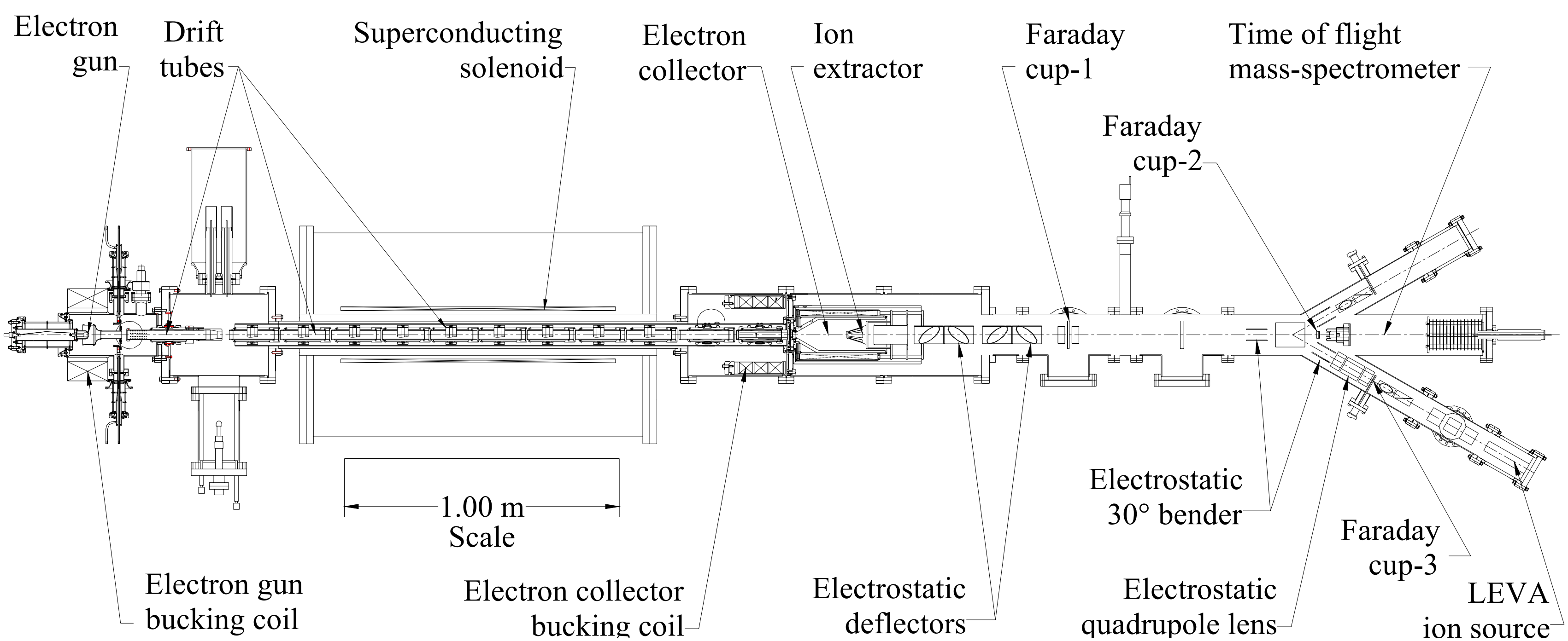
   (Note - 1 & 3 result in a Au^{32+} current of 1.6 - 0.4 mA)

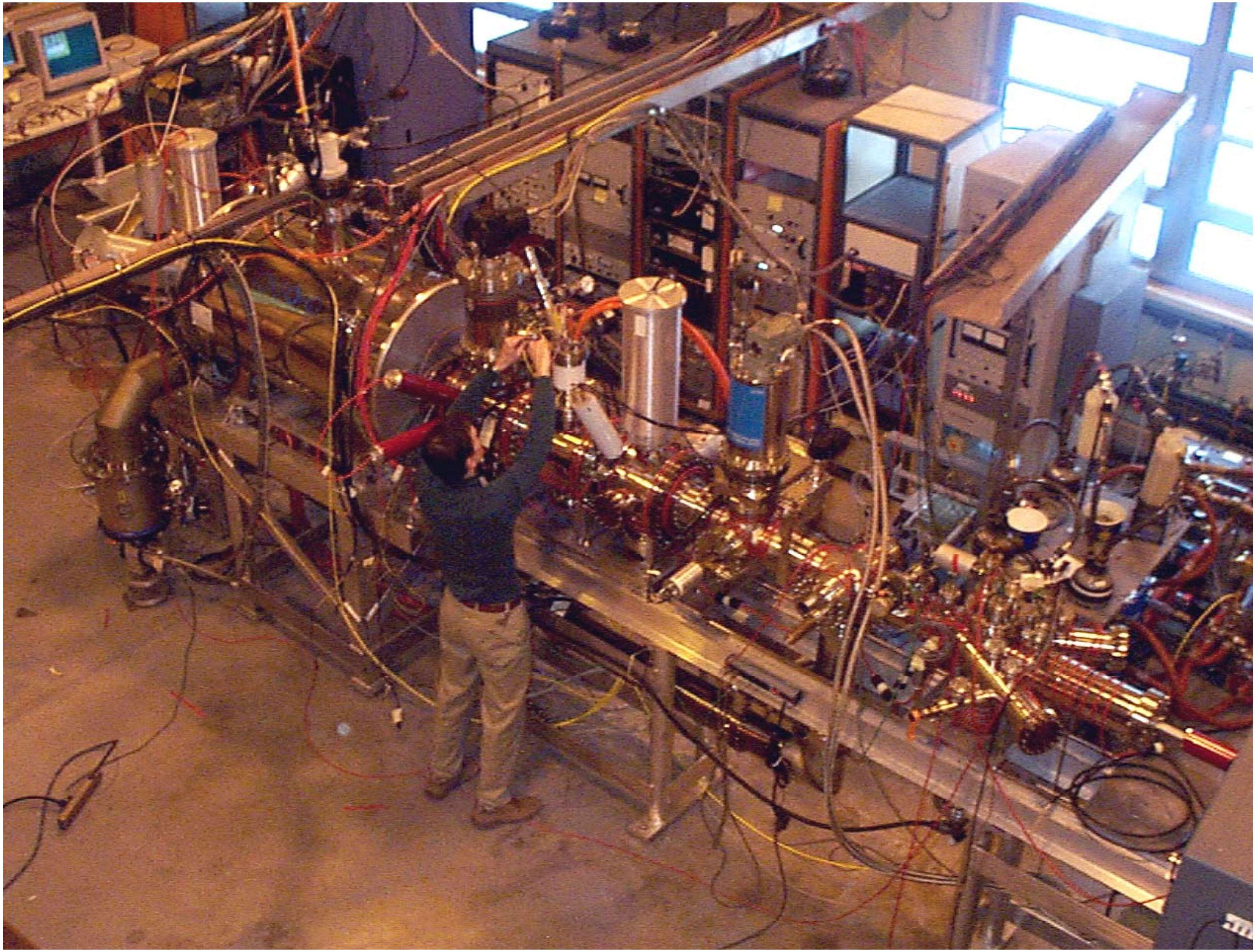
4. Rep rate : ~ 10 Hz

5. Emittance : ≤ 0.35 π mm mrad, normalized, 90% (for low loss at Booster injection)

The intensity requirement for this EBIS was > 20 times that ever achieved previously, so an R&D program was started at BNL to demonstrate the required performance.

EBIS Test Stand - showing ion injection, and extraction to TOF





EBIS Test Stand

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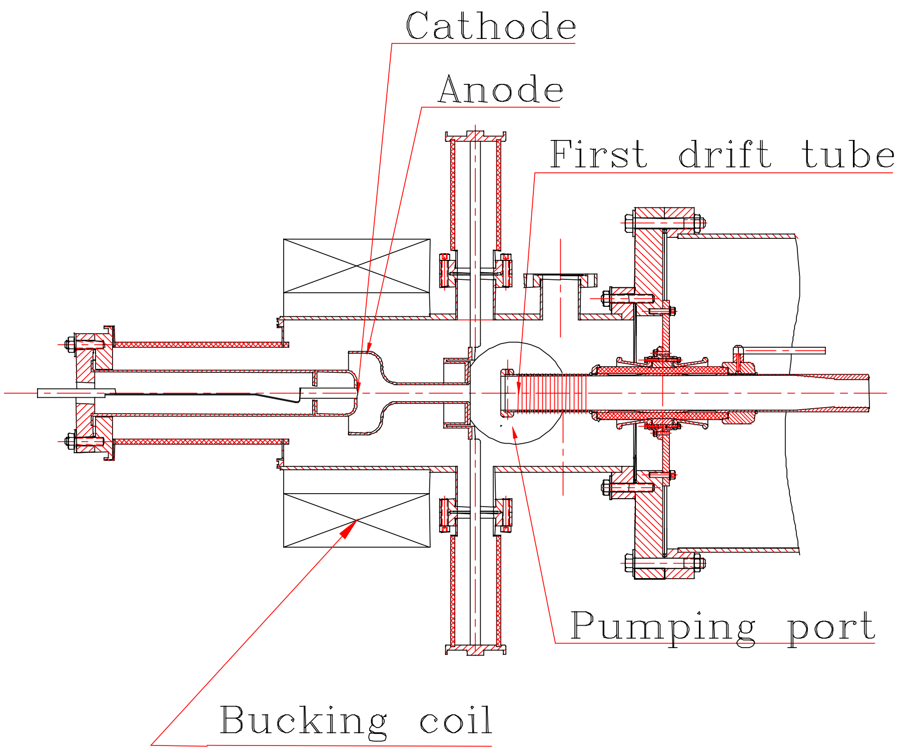
Key hardware features of the EBTS

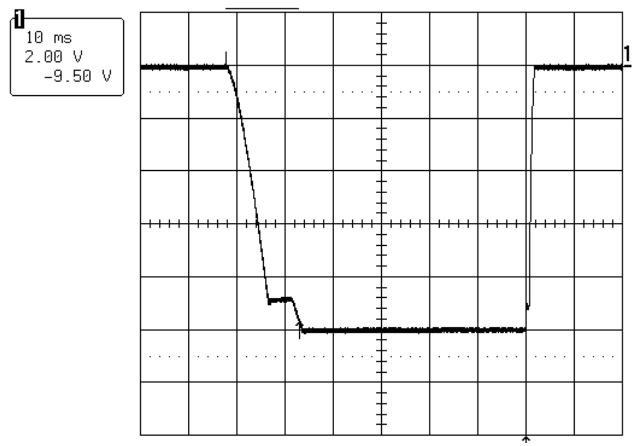
Superconducting solenoid:	
Length	**1 meter**
Maximum field	**5 Tesla**
Bore	**155 mm diameter, warm**
Helium consumption	**0.12 l/hr**
Drift tubes:	
No. of electrodes	**12**
Bore diameter	**31 mm**
Trap length	**0.7 m**
Electron gun cathode	**LaB_6, 8.3 mm diameter**
Electron collector power	**50 kW**
Vacuum	**1 x 10^{-9} to 4 x10^{-10} Torr in most regions (most sections bakeable to 200C, central DT's to 450 C)**
Diagnostics:	
Time-of-flight	**Mamyrin-type, 2 m from ion extractor**
Faraday cups	**0.5 and 1.5 m from ion extractor**
Harp	**1.6 m from ion extractor**
Emittance	**1.6 m from ion extractor (under development)**

<u>Development of the 10 A electron gun</u> – This was a key element, since previous EBIS operation was typically at 0.5 A or less. **Collaboration with BINP on the development of a LaB_6–based electron gun. This gun has produced currents of up to 13A, has a good lifetime, and excellent beam optics. The unique optics for extraction and matching into the strong magnetic field allows a very stable operation over a broad range of electron beam currents.**

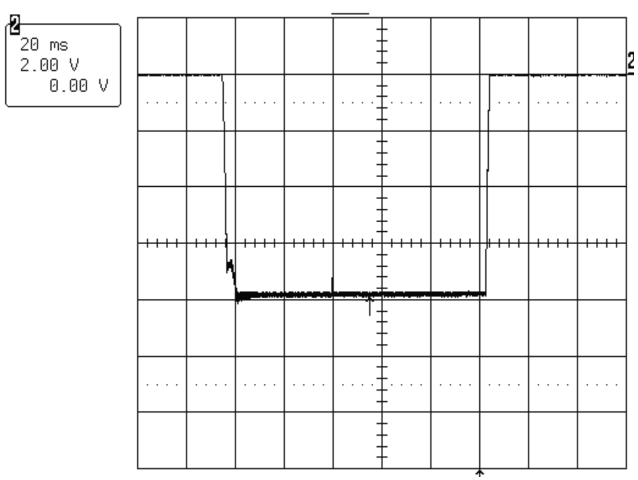


<u>Propagation of a 10 A electron beam through the EBIS trap</u>

10 A, 50 ms Electron Beam Pulse

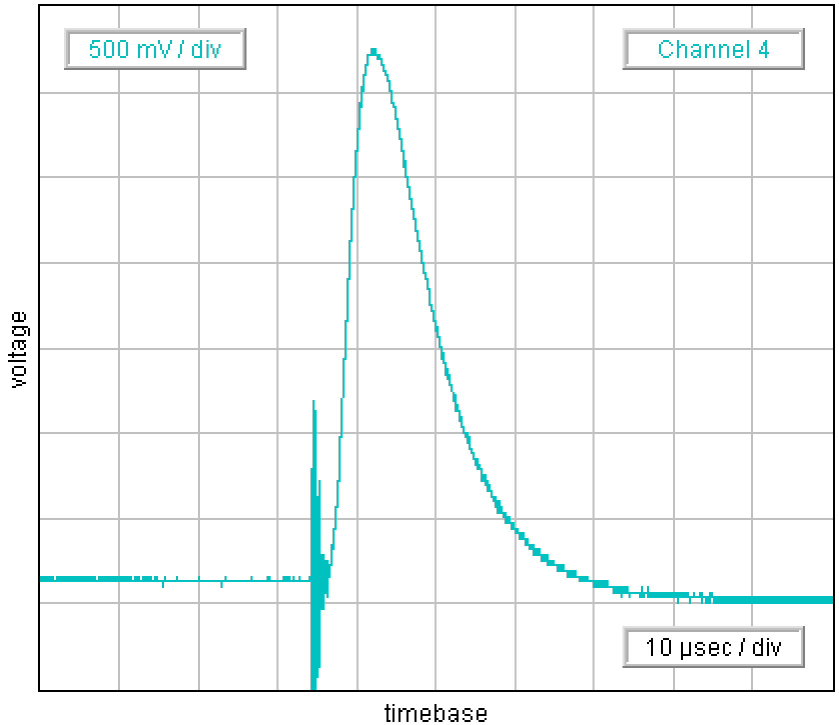


8 A, 100 ms Electron Beam Pulse



Electron Gun Cathode Assembly

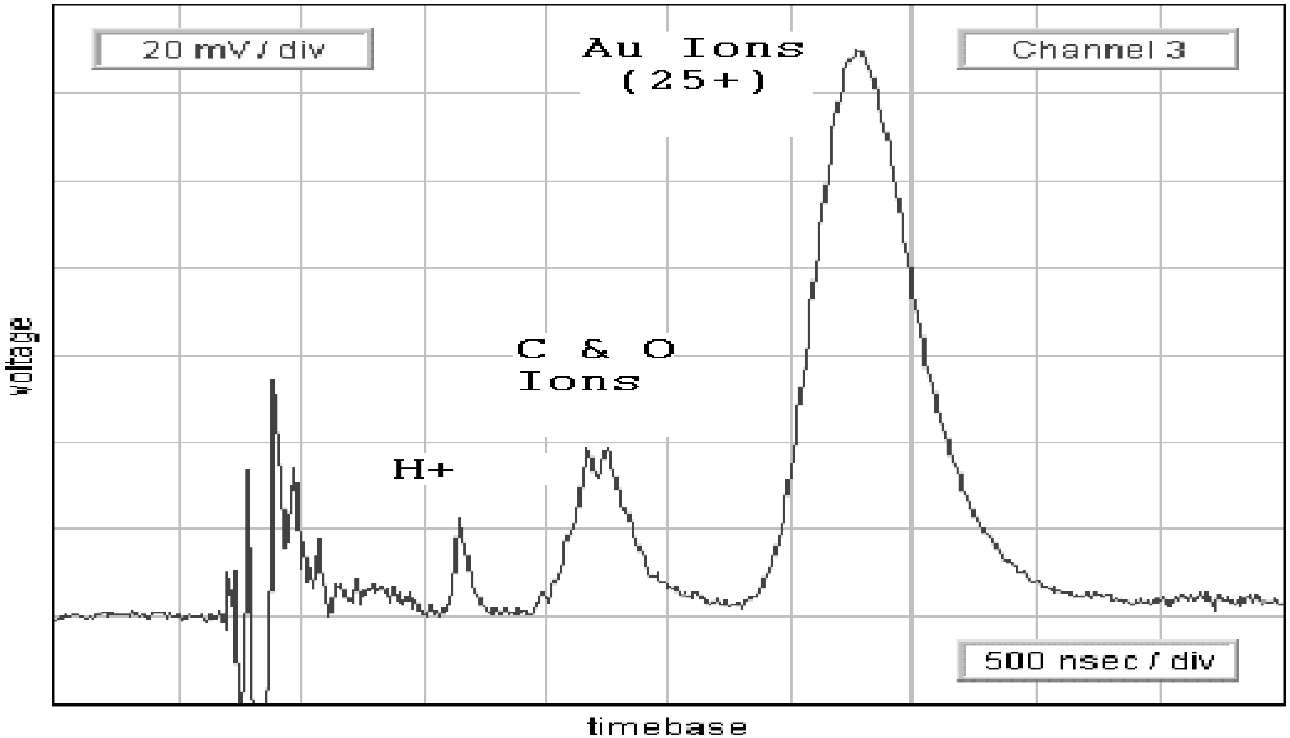
Fast Extraction of Ions from the EBTS
(for single turn injection into Booster)



A 3.2mA, 12μs FWHM, (40nC) ion pulse was obtained at the source exit toroid using a 6.8A e-beam and Au external ion injection, after a 15ms confinement. (85 nC required for RHIC)

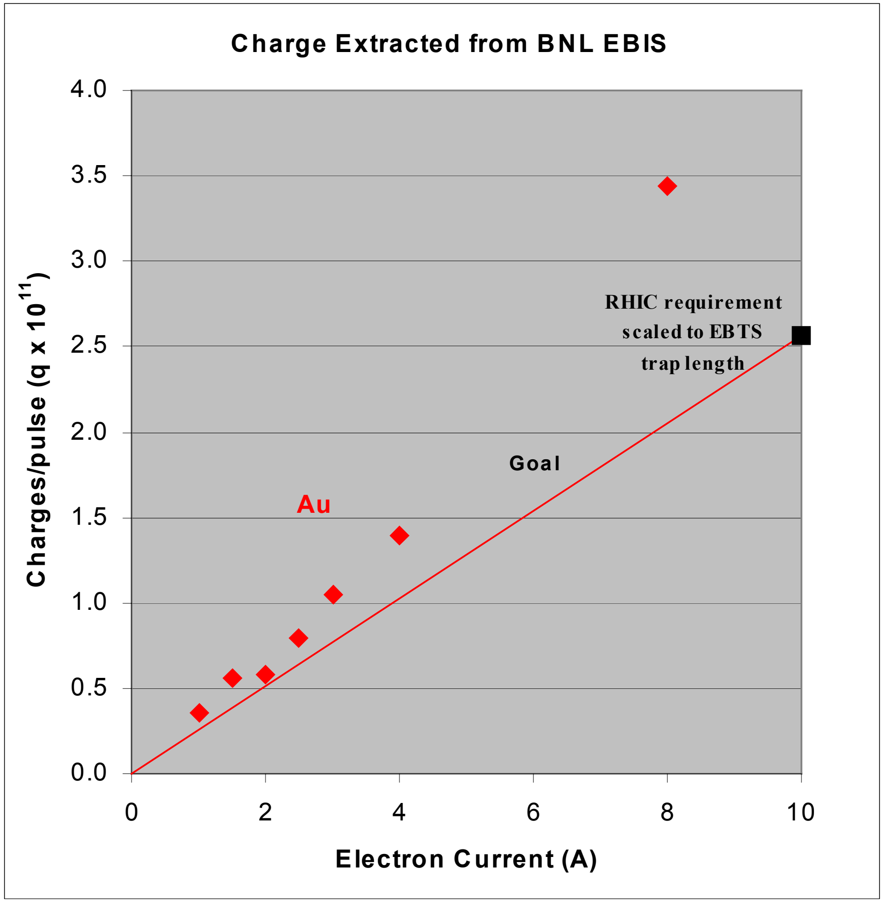
Faster extraction has been obtained earlier by applying a gradient to the well floor during extraction. In the future, the pulse shape will be tailored by applying an appropriate voltage pulse to the well.

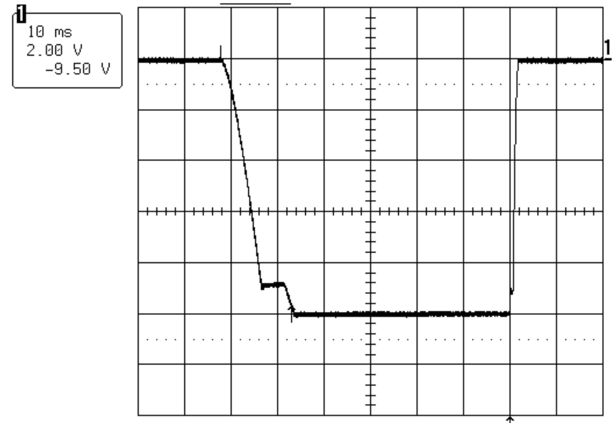
Inline Time-of-Flight



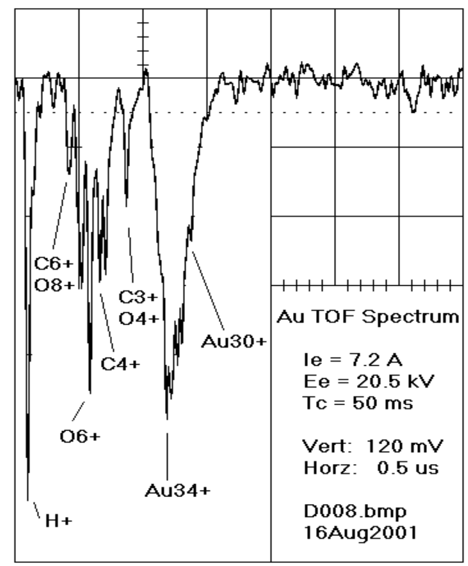
- Full ion beam, sampled and collected on a Faraday cup
- I_e= 7A;
- 10 ms confinement
- Au = 83%; C&O = 15%; H = 2%

Results from Test EBIS (½ Length of RHIC EBIS)





10 A, 50 ms Electron Beam Pulse

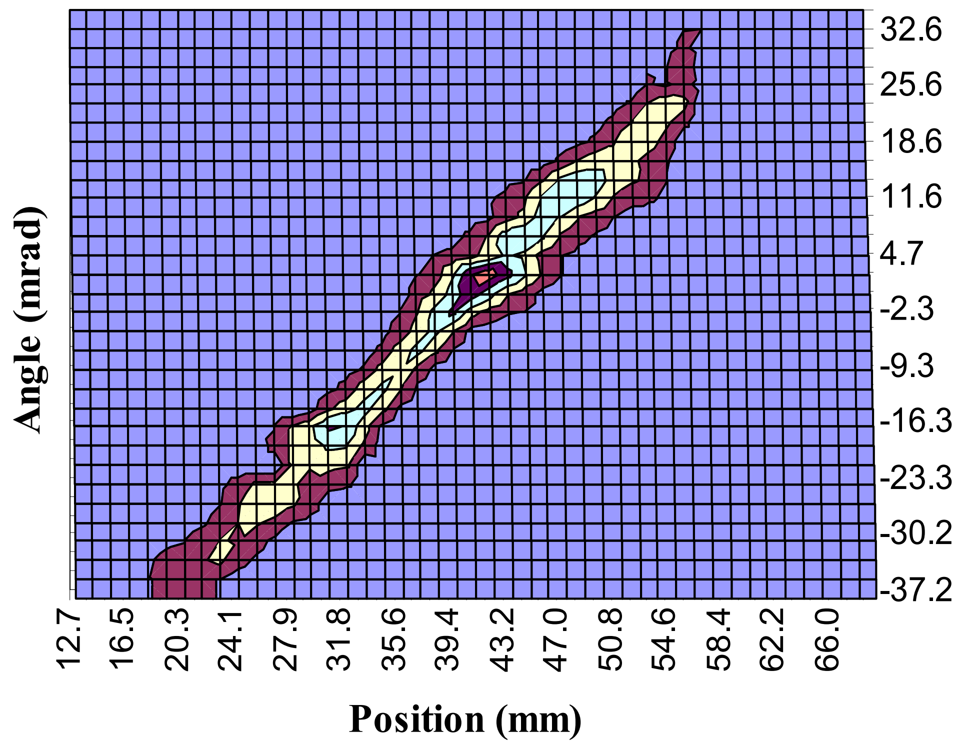


Time-of-flight spectrum peaked at Au 34+

5.5 x 10^{11} charges/pulse are required for RHIC. By doubling the EBIS trap length to 1.5 m, we will exceed this requirement. (The ion yield has been shown to scale linearly with trap length).

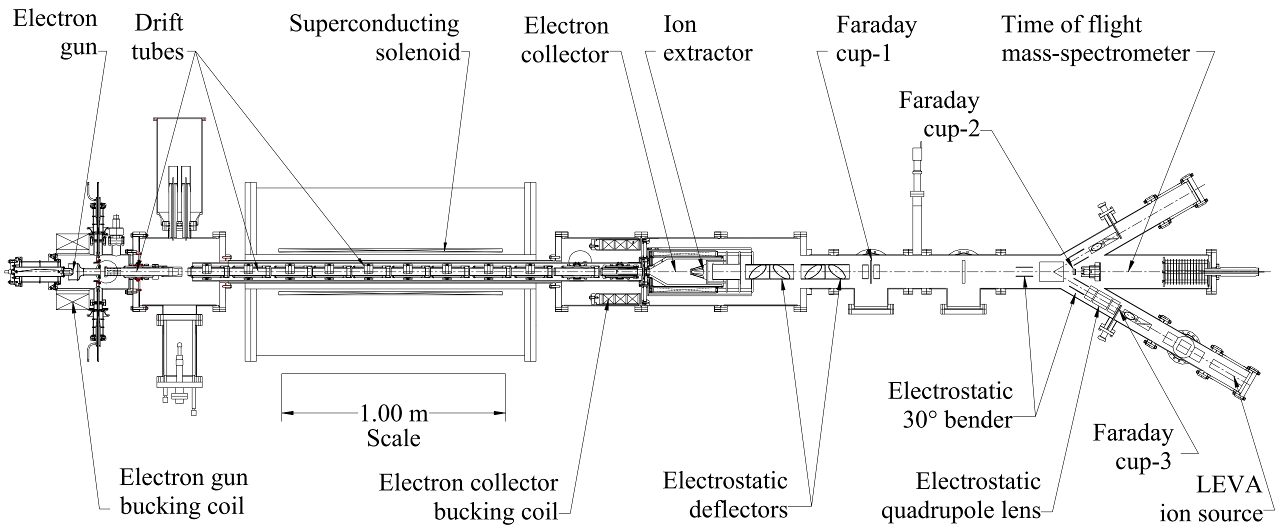
Emittance

(initial test; we need to develop better measurement device)



Emittance of a 1.7 mA extracted beam from EBIS, with Au injection. ε (n, rms)= 0.1 π mm mrad.

Results from Test EBIS (½ of RHIC EBIS)



	RHIC Requirements	Achieved
E-beam current	10 A	10 A
E-beam energy	20 keV	20 keV
Yield of pos. charges	5.5×10^{11} (Au, 10 A, 1.5m)	3.2×10^{11} (Au, 8 A, 0.7m)
Pulse length	$\leq 40\ \mu s$	$20\ \mu s$
Yield of Au^{33+}	3.4×10^{9}	$\sim 1.5 \times 10^{9}$

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EBIS Status

	Achieved	**RHIC**
Ion	Au^{32+}	Au^{32+}
$\mathbf{I_e}$	10 A	10 A (15)
$\mathbf{J_e}$	500 A/cm^2	500 A/cm^2
$\mathbf{t_{confinement}}$	35 ms	35 ms
$\mathbf{L_{trap}}$	0.7 m	1.5 m
Capacity	0.51 x 10^{12}	1.1 x 10^{12}
% extracted ions	> 75%	50%
% in desired Q	20%	20%
Extracted charge	> 55 nC	85 nC
Ions/pulse	> 1.5 10^9 (Au^{32+})	3.3 x 10^9 (Au^{32+})
Pulse width	10-20 μs	10-40 μs

the Bulletin

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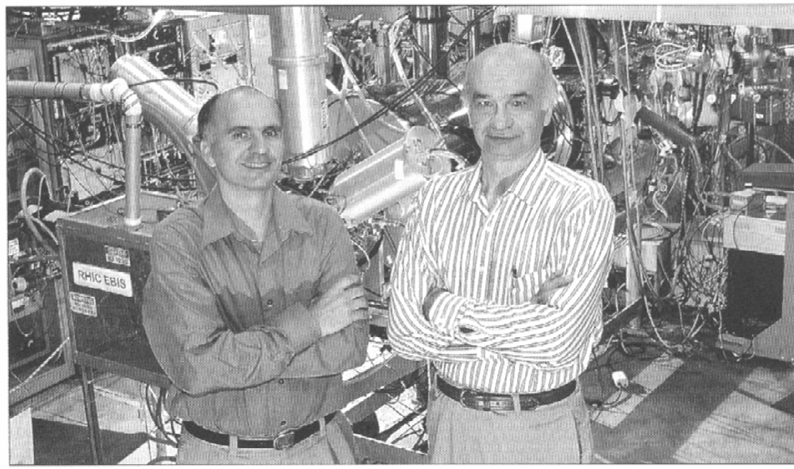
Vol. 57 - No. 35 October 10, 2003

Edward Beebe and Alexander Pikin Win 'Brightness Award' For Achievement in Ion Source Physics, Technology



Roger Stoutenburgh 00040903

Edward Beebe (left) and Alexander Pikin stand in front of the electron beam ion source that they developed and tested at Brookhaven Lab.

Edward Beebe and Alexander Pikin, physicists in the Collider-Accelerator Department, have been awarded the Ion Source Prize, known as the "Brightness Award," which recognizes and encourages innovative and significant recent achievements in the fields of ion source physics and technology.

The two physicists received the award on September 9, at the Tenth International Conference on Ion Sources, held in Dubna, Russia. Donated by Bergoz Instrumentation of Saint Genis Pouilly, France, the award consists of $6,000, to be shared by the two winners, and a certificate for each.

An ion is an atom that has a net excess or deficit of electrons, allowing it to be manipulated by electric and magnetic fields. Ions are accelerated to nearly the speed of light for physics research in accelerators, such as the Relativistic Heavy Ion Collider (RHIC). Funded by the DOE's Office of Science, Nuclear Physics, Beebe and Pikin have developed and tested a new high-intensity version of a source that produces highly charged heavy ions, called an electron beam ion source. The number of ions generated by this source is twenty times more than in previous designs. BNL plans to eventually use a version of this source for ion injection into RHIC. In addition, the new ion production method may be adapted for use in other particle accelerators, such as the Large Hadron Collider at CERN, the European laboratory for particle physics.

Since 1970, two accelerators at Brookhaven, known as the Tandem Van de Graaff, have provided researchers with heavy ions. The new method for producing ions would require only a small linear accelerator, about one-tenth the size of the Tandem Van de Graaff.

The new combination of ion source and accelerator will provide enhanced performance and will be easier to operate and maintain than the current method for ion production. The new source is able to directly create and accelerate highly charged positive ions. In contrast, the Tandem must begin by accelerating negative ions; stripping foils are then used to make the highly charged positive ions required for RHIC experiments. In addition, the new source is more versatile than the current method, since it can produce ion beams of any species.

For more information, see www.bnl.gov/bnlweb/pubaf/pr/2003/bnlpr090903a.htm.

— Diane Greenberg

387th Brookhaven Lecture, 10/15

Received at 10th International Conference on Ion Sources (Dubna)

EBTS performance represents more than an order of magnitude improvement over past EBIS sources. At the same time, operation has been very reproducible and stable. Some of the key features, almost all of which are unique to this EBIS, are the following:

•A novel electron gun design from Novosibirsk. It uses a convex LaB_6 cathode

(produces a low rotational electron beam well suited for the accelerations and decelerations common in the EBIS transport system)

•A warm bore, unshielded superconducting solenoid for the main trap region

•Careful vacuum separation of the trap region from the electron gun and electron collector regions

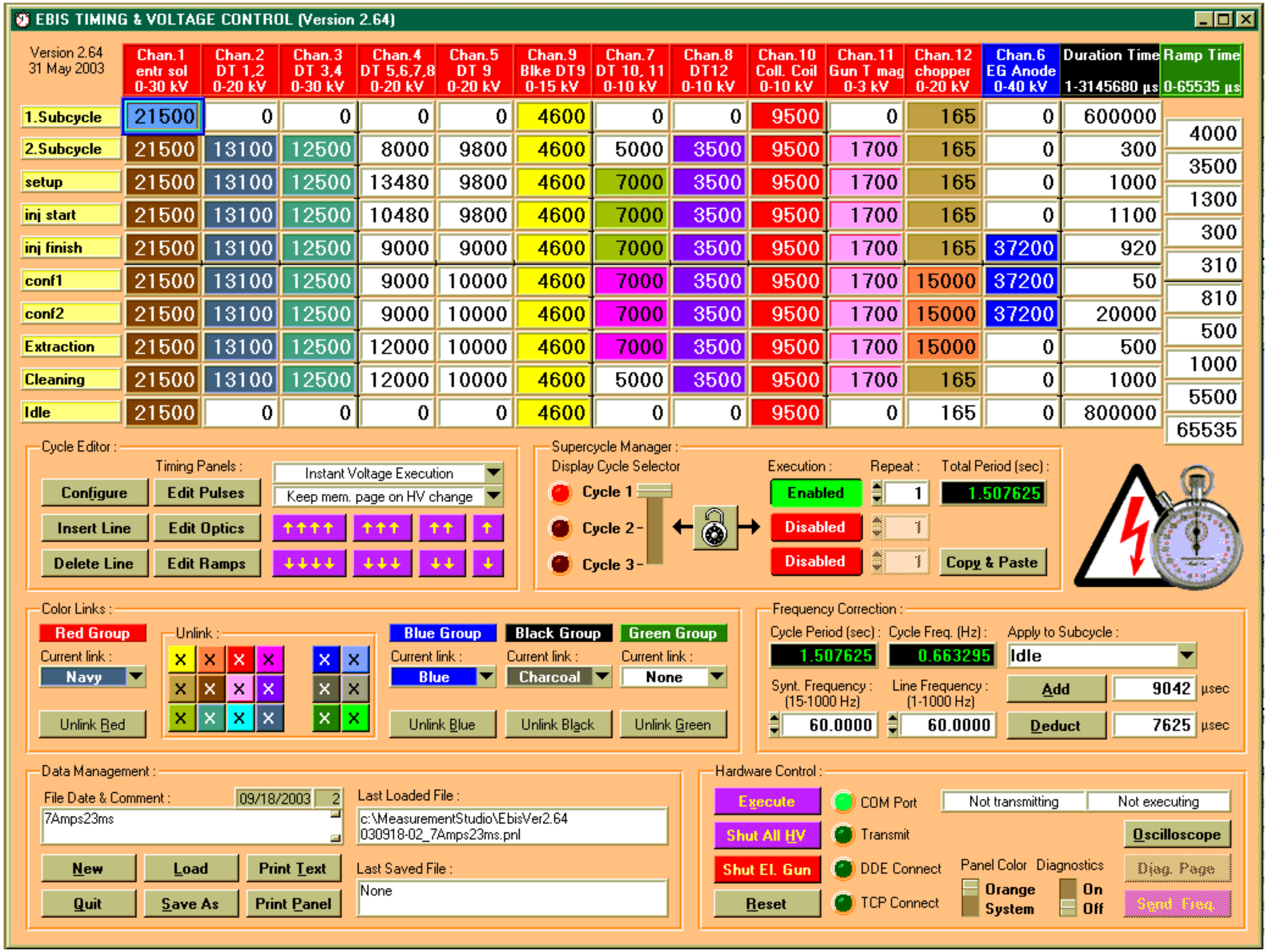
•Large bore (32mm) drift tubes have been used (pumping, reduced alignment precision, fast extraction, reduced RF coupling)

•The use of auxiliary (warm) solenoids & many transverse magnet coils for steering corrections

•The electron beam is pulsed to reduce the average power on the electron collector

•Very versatile controls allow one to easily apply a time dependent potential distribution to the ion trap

Screen for controlling EBIS electrode voltages during a cycle



Parameters for the RHIC EBIS are the following:

Output (single charge state):	1.1 x 10^{11} charges
Ion output (Au32+):	3.4 x 10^{9} particles/pulse
Pulse width:	10 - 40 μS
Max rep rate:	10 Hz
Beam current (single charge state):	1.7-0.42 mA
Output energy:	8.5 keV/amu
Output emittance:	0.35 π mm mrad, norm, 90%

The primary difference in the RHIC EBIS, compared to EBTS, is the doubling of the trap length to double the ion output. Other new features we plan to incorporate into the final EBIS will be made in order to make the final EBIS more robust.

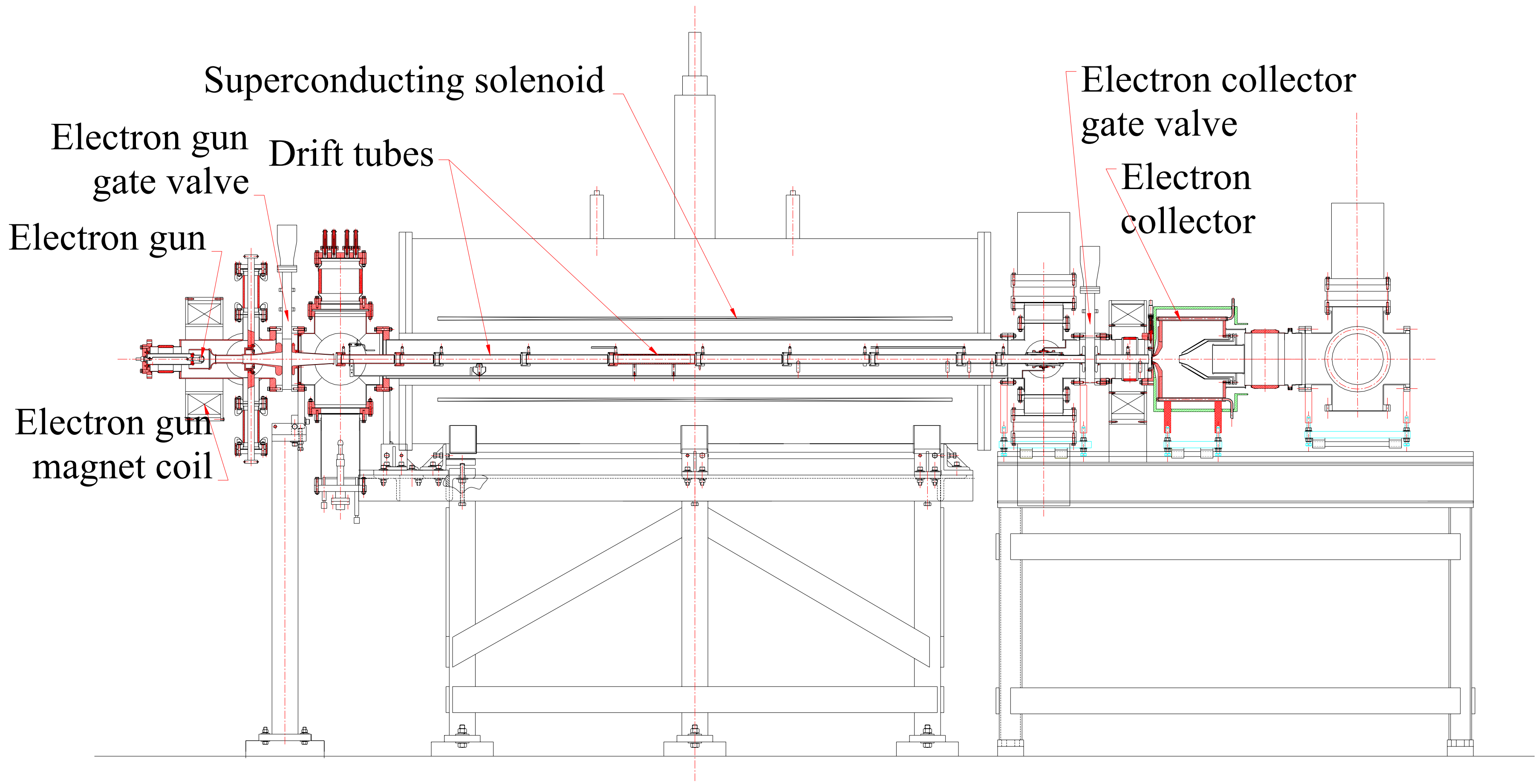
Superconducting Solenoid: the solenoid length will be increased from 100 cm to 200 cm. The field will remain at 5 T, but the bore will be increased from 155 mm diameter to 204 mm diameter, in order to facilitate pumping in the longer trap region.

Electron Gun: While the existing 10 A unit meets the RHIC EBIS requirements, to have a more comfortable safety factor and a reserve for a possible future increase of the ion beam intensity, we are developing a 15 A gun design. We plan to test a cathode unit based on IrCe rather than the present LaB_6, in collaboration with the Budker Institute of Nuclear Physics (BINP).

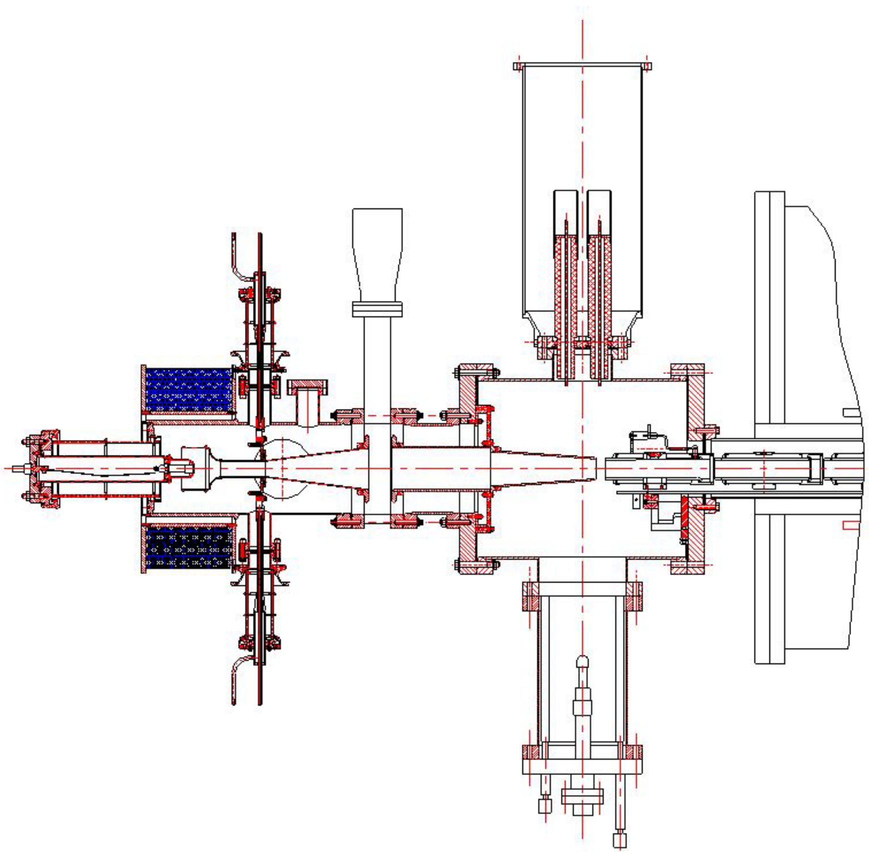
Electron Collector: The main improvement in the new electron collector (EC) for the RHIC EBIS is an increase in its capacity to dissipate power. The new EC will be designed to dissipate a power of 230 kW, higher than our expected load of 100 kW. The longitudinal distribution of the electron beam on this surface will be made more homogeneous.

Vacuum: Efficient vacuum separation between the sections. Gate valves separating the central region containing the ion trap from electron gun and electron collector regions. Increased vacuum conductivity between the middle part of the central chamber and the ends where pumps are located, by increasing the diameter of the central chamber from 4” (as it is now in EBTS) to 6”. The use of non-evaporable getters (NEG) in the region of the ion trap is also being considered.

Schematic of EBIS for RHIC

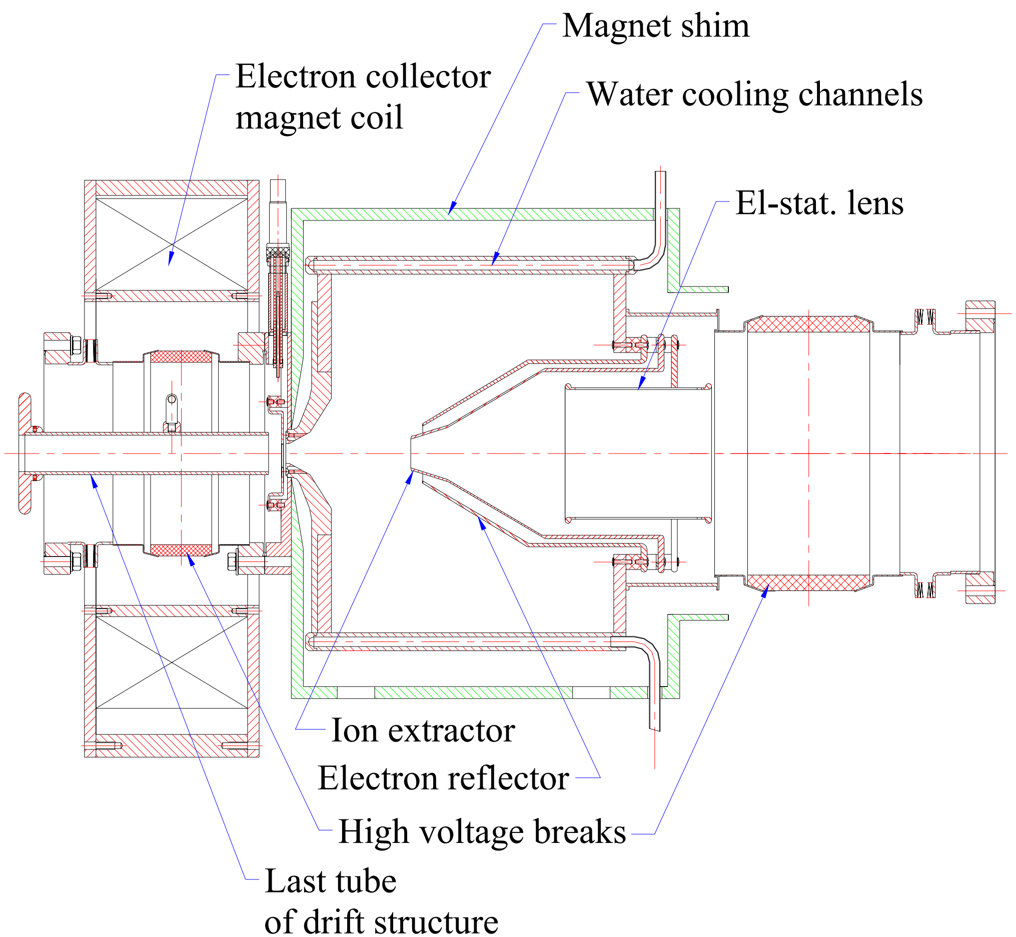


Gun Gate Valve and Anode Modification



- Allows cathode replacement and electron gun upgrades without disturbing ionization volume ultra-high vacuum.
- Anode/Drift Tube geometry eliminates need for an additional auxiliary solenoid
- Electron beams up to 7A have been propagated with very low loss.
- IrCe Cathodes have been delivered from BINP, Novosibirsk. They will be installed at the EBTS for electron beam tests.

New Collector Concept:



Designed to dissipate 230 kW

More uniform distribution of e-beam

Increased surface area (2200 cm^2)

Estimated max power density = 385 W/cm^2

Outer surface of collector is at atmosphere (~ no internal cooling lines).

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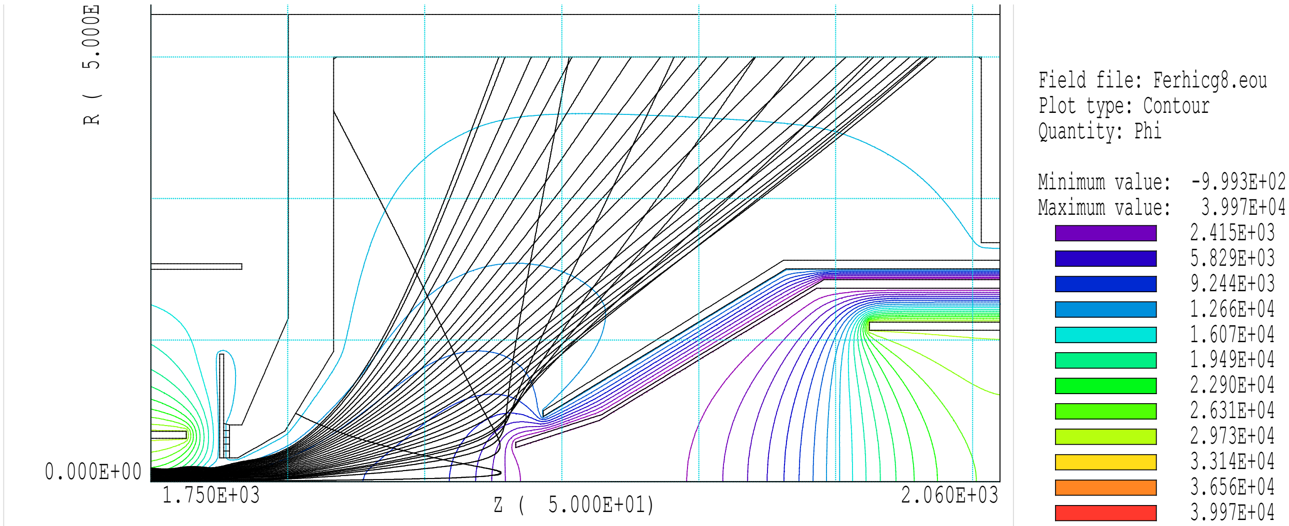
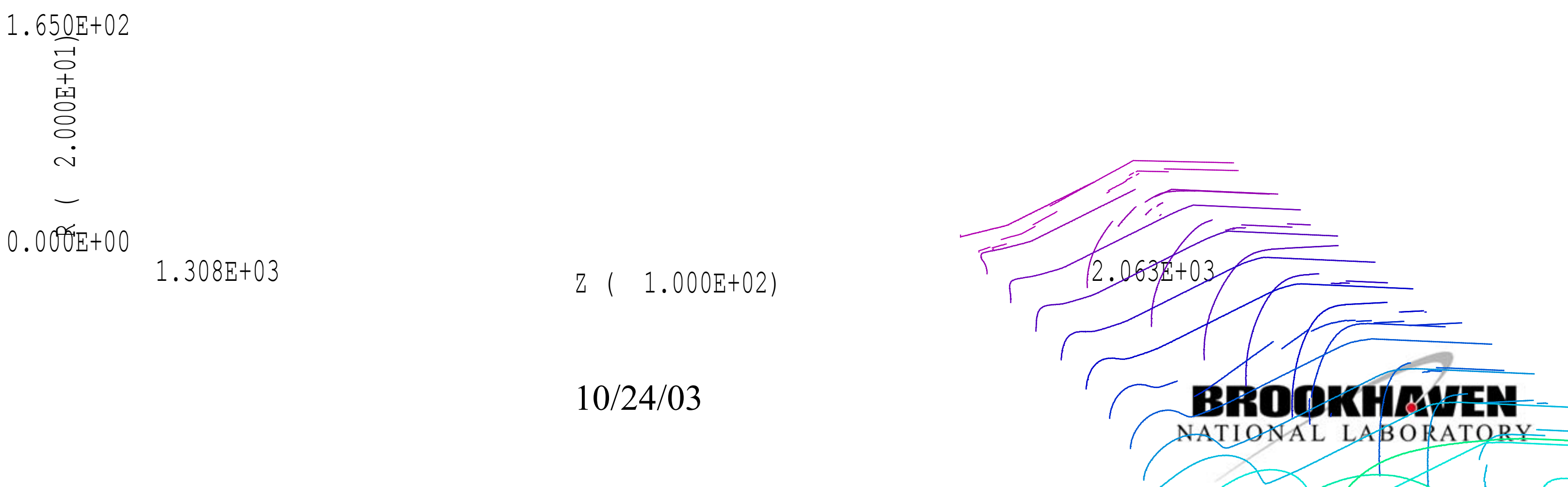
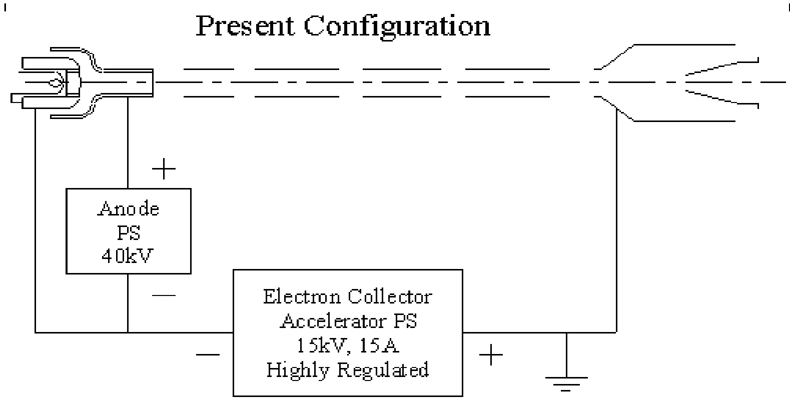
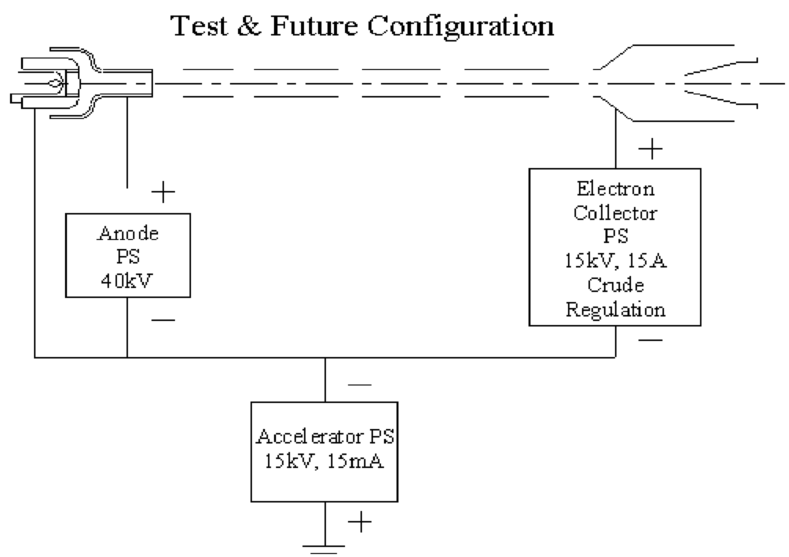
Work on an electron gun/collector design to spread the beam more uniformly in the collector:





Unregulated Collector Supply





- Unregulated, high current supply for electron beam collection
- Low current regulated supply provides
  1) stable e-beam launch
  2) Independent acceleration voltage
  3) Electron beam fault protection
- 50μF Capacitor "Collector Supply"
  4A electron beam, 50ms pulse
  droop ~3.7kV from nominal 10kV
- Good e-beam propagation
- Ion Injection and extraction will be locked to repetitive waveform to minimize optical effects

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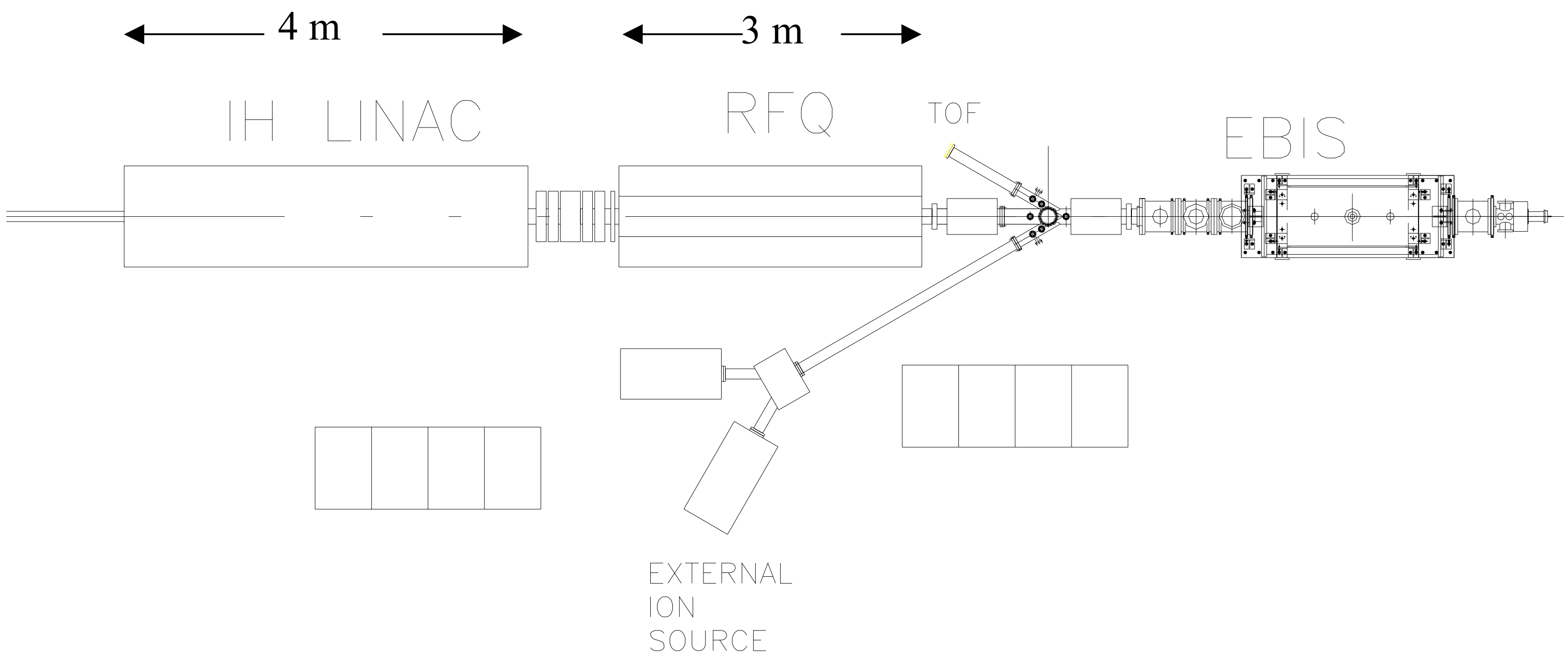
Superconducting Solenoid Requirements

	RHIC EBIS	EBTS
Guaranteed maximum magnet field:	5 T (tested to 5.5 T)	5T (tested to 5.5)
Inner diameter of the warm bore	204 mm (clearance for 8" flange)	155 mm (clear for 6")
Total length of solenoid	2000 mm	1000 mm
Homogeneity over region 1300x10mm	0.25%	0.25%
Maximum radial shift of magnet field axis over full length of the magnet (documented)	0.2 mm	0.2 mm
Maximum radial deviation of position of solenoid axis from the position of warm bore axis	0.2 mm	0.2 mm
Decay rate of magnet field in coils of solenoid, operating with current leads removed.	1×10^{-6} per hour	1×10^{-5} per hour
Length of vacuum jacket	~ 2300 mm	1300 mm
Period between liquid helium refills	30 days	23 days
Period between liquid nitrogen refills	10 days	12 days

Plans for this year

- Test IrCe cathode for higher current operation, better lifetime
- Evaluate sources for primary ion injection
  - Already testing LEVA (free from LBL), Hollow Cathode (free from Saclay)
  - Future: Chordis, FEBIAD, small ECR?
- Try alternate collector PS configuration (cheaper, more stable)
- Source on HV platform (for future RFQ injection)
- Emittance studies
- Ion extraction optics optimization
- LEBT – layout design, solenoids or einzel lenses?
- New collector design to handle higher power and get cooling lines out of the vacuum
- Start design of 2 m SC solenoid?
- Test feedforward for extracted ion pulse shaping
- Off-axis electron gun ?? (similar to e-cooling)

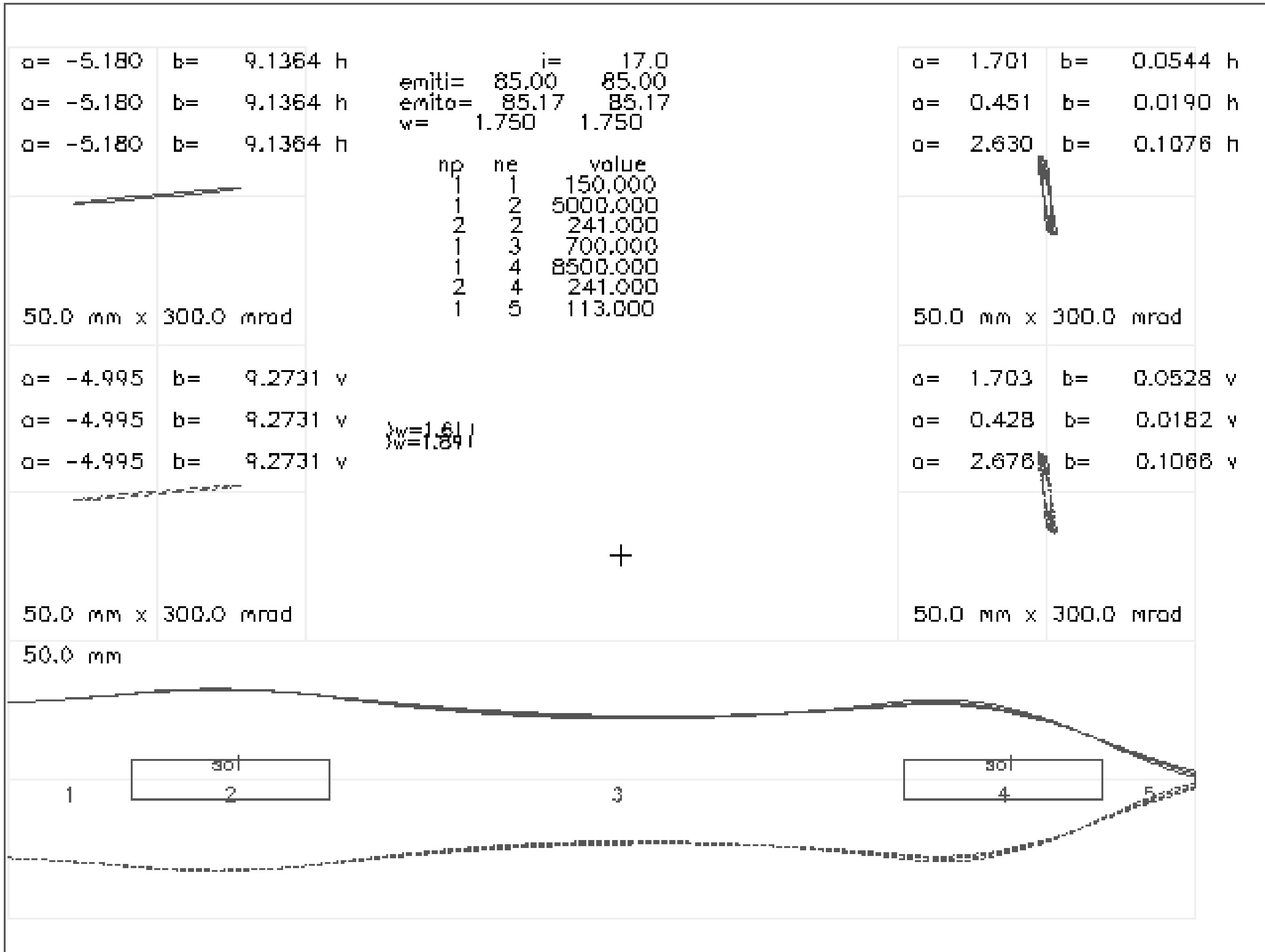
Proposed Linac-based RHIC Preinjector



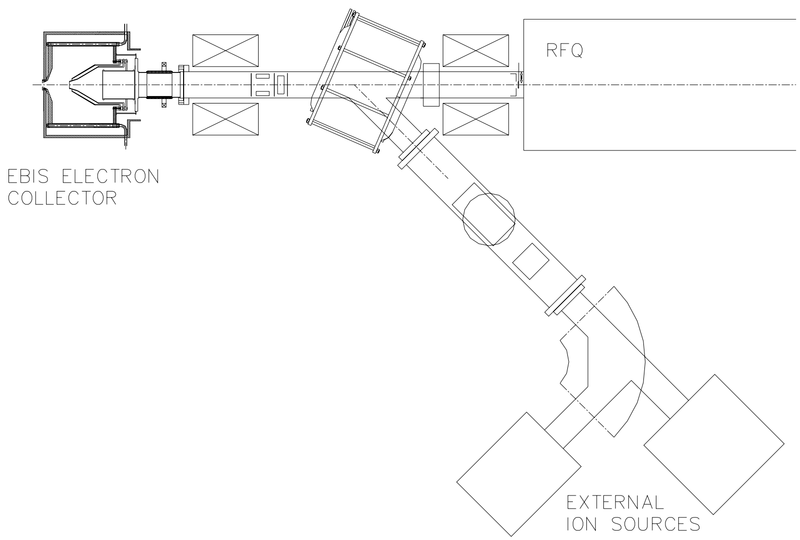
RFQ: 8.5 - 300 keV/u; 100 MHz

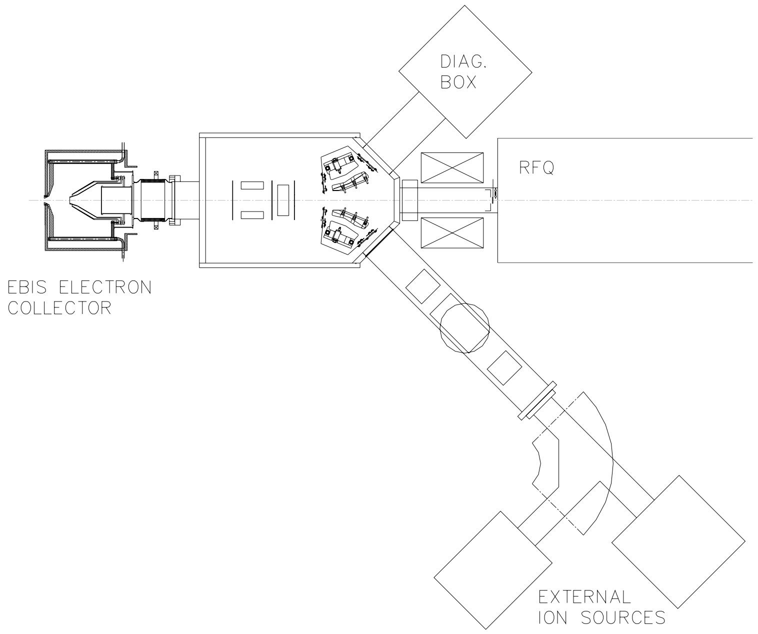
Linac: 0.3 - 2.0 MeV/u; 100 MHz

LEBT Optics (Solenoid focusing)



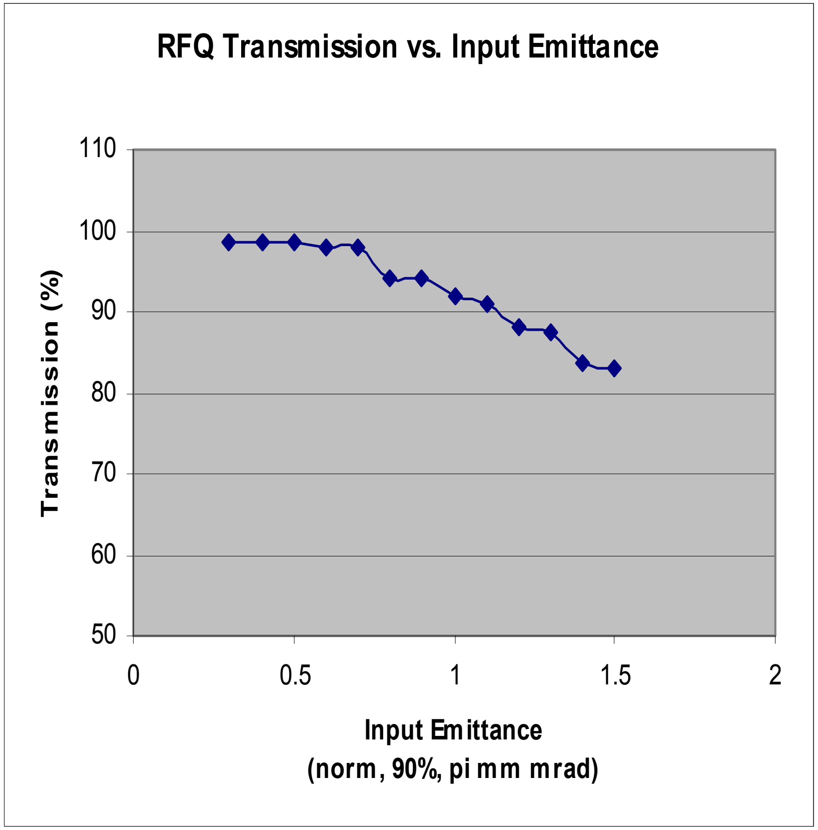
Presently investigating possible layouts for LEBT





RFQ Parameters

Parameters	BNL	CERN	Units
Type	4-rod	4-rod	
Q/m	0.16-0.5	0.12	
Input Energy	8.5	2.5	keV/amu
Output Energy	300	250	keV/amu
Frequency	101.28	101.28	MHz
Max rep rate	10	10	Hz
Length	2.96	2.5	Meters
Number of cells	236		
Aperture Radius	0.006	.0045	Meters
Voltage	92	70	kV
E (surface)	20.8	≤23	MV/m
RF Power	< 350	< 350	kW
Acceptance	1.7	> 0.8	pi mm mrad (nor)
Input Emittance	0.35		pi mm mrad, nor, 90%
Output Emittance (trans)	0.375		pi mm mrad, nor, 90%
Output Emittance (longit)	0.75		pi MeV deg
Transmission	97	93	%
Bravery factor	1.8	≤ 2	Kilpatrick



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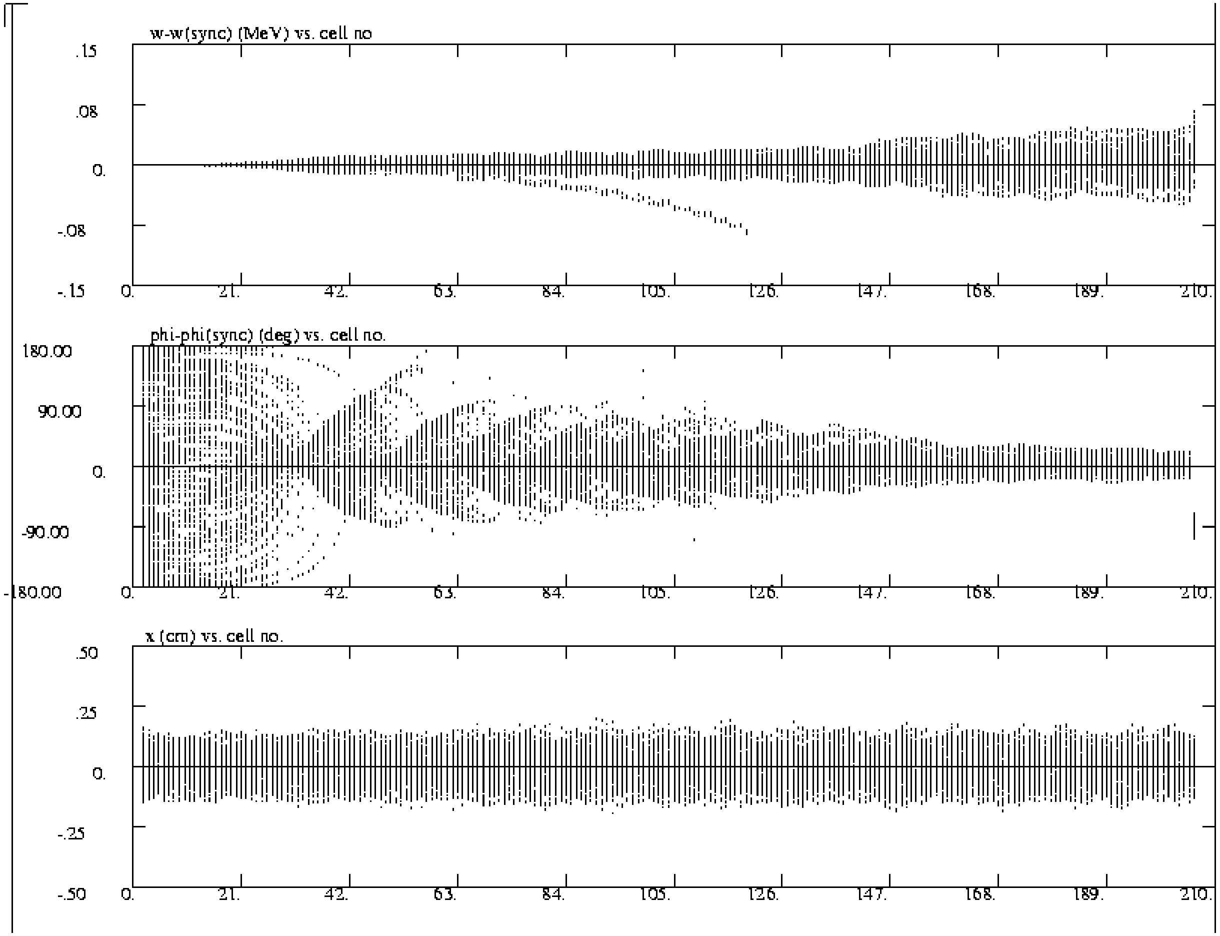
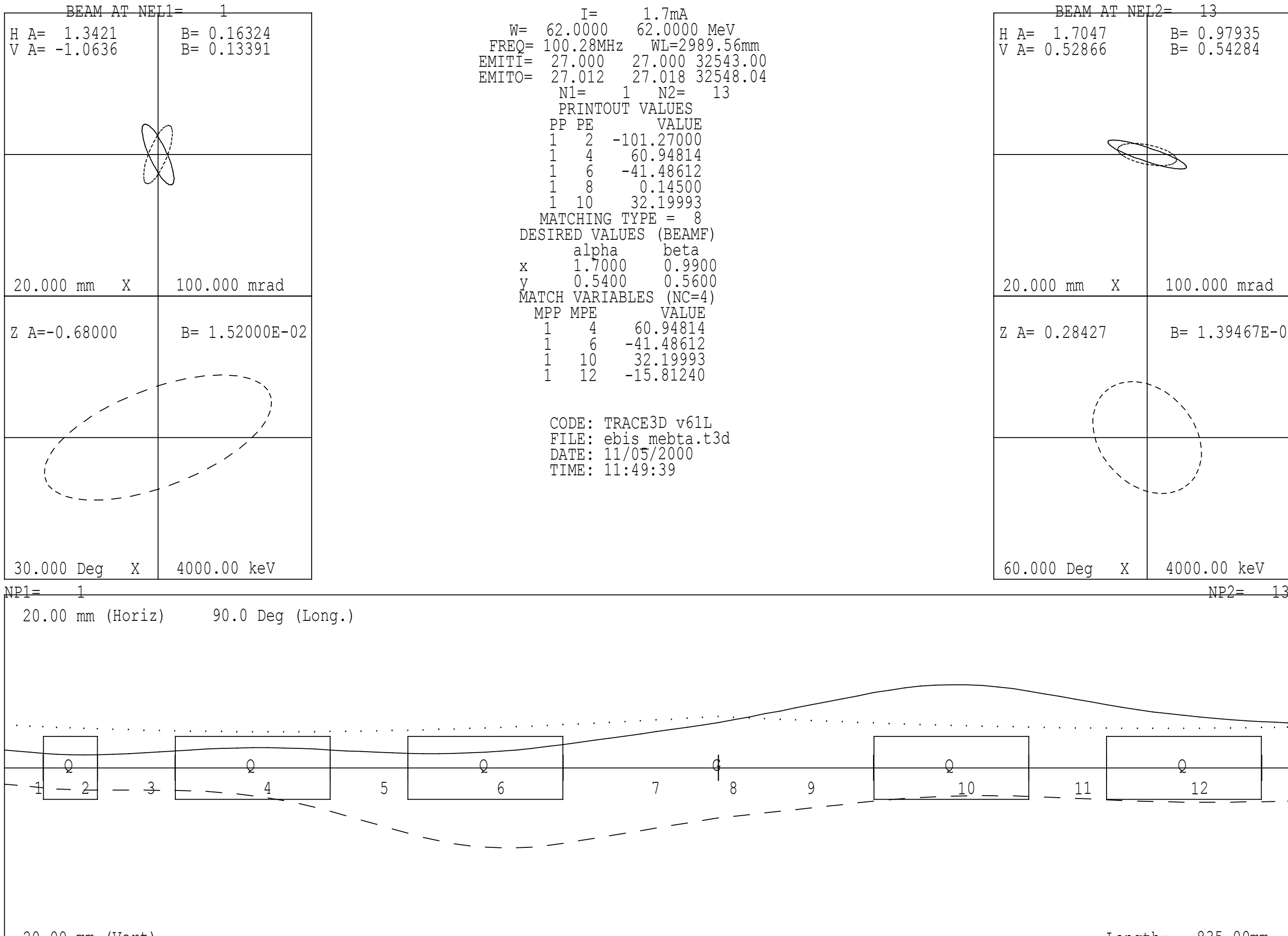
RFQ Beam Dynamics Design



(Present thinking – collaboration with Frankfurt on a 4-rod RFQ)

Transport from RFQ to Linac
(5 quads, 1 buncher)



Linac

IH Linac, very similar to the first tank of the CERN Pb linac, is our baseline:

Table6: Main parameters of the IH linac

Parameters	**BNL**	**CERN Tank 1**	**Units**
Q/m	0.18-0.5	0.12	
Input energy	0.300	0.250	MeV/amu
Output Energy	2.0	1.87	MeV/amu
Frequency	101.28	101.28	Mhz
Max rep rate	10	10	Hz
length	4.0	3.57	Meters
Input emittamce	0.55		pi mm mrad, norm,90%
Output emittance	0.61		pi mm mrad, norm,90%
Output energy spread	20.0		keV/amu
transmission	100		%

The other linac option, a superconducting linac similar to ATLAS, has been set aside for now due to its higher cost.

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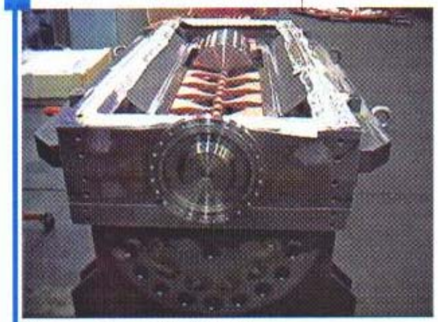
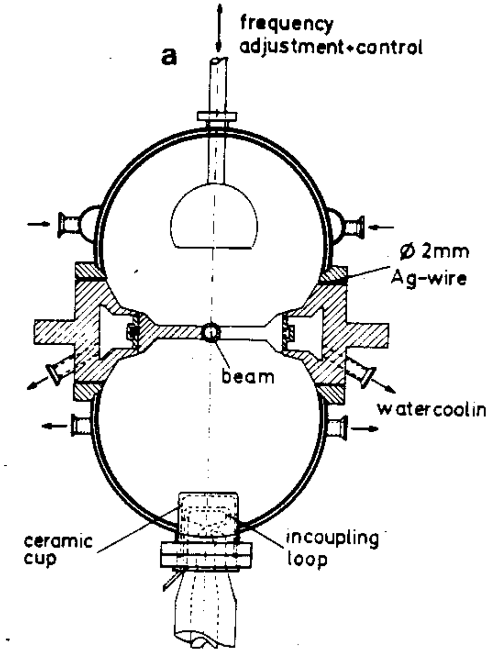
IH-Resonator for the REX-ISOLDE Project



Mid section with drift tubes

Section with drift tubes during measurement of the resonance frequency

Watercooled top section of the IH-Resonator



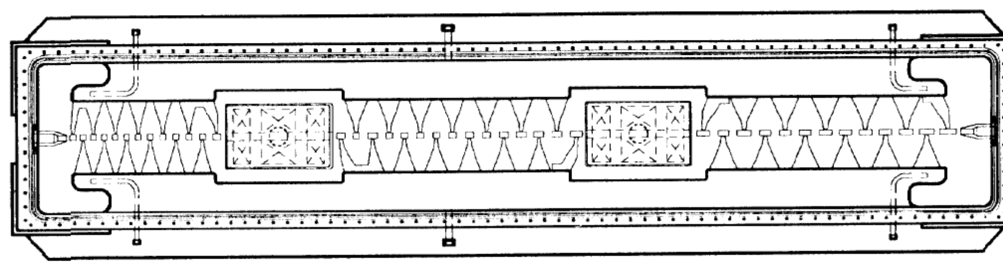
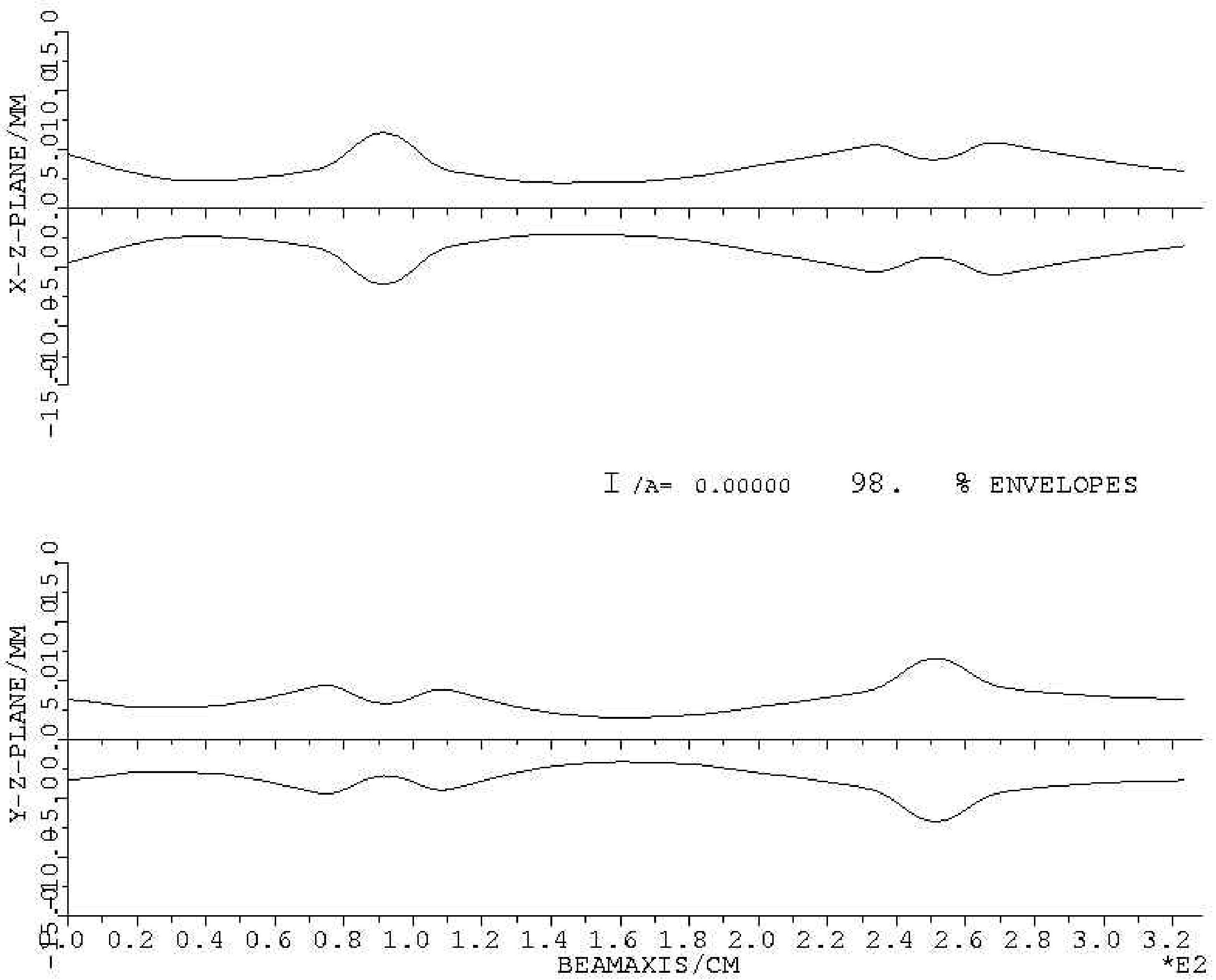
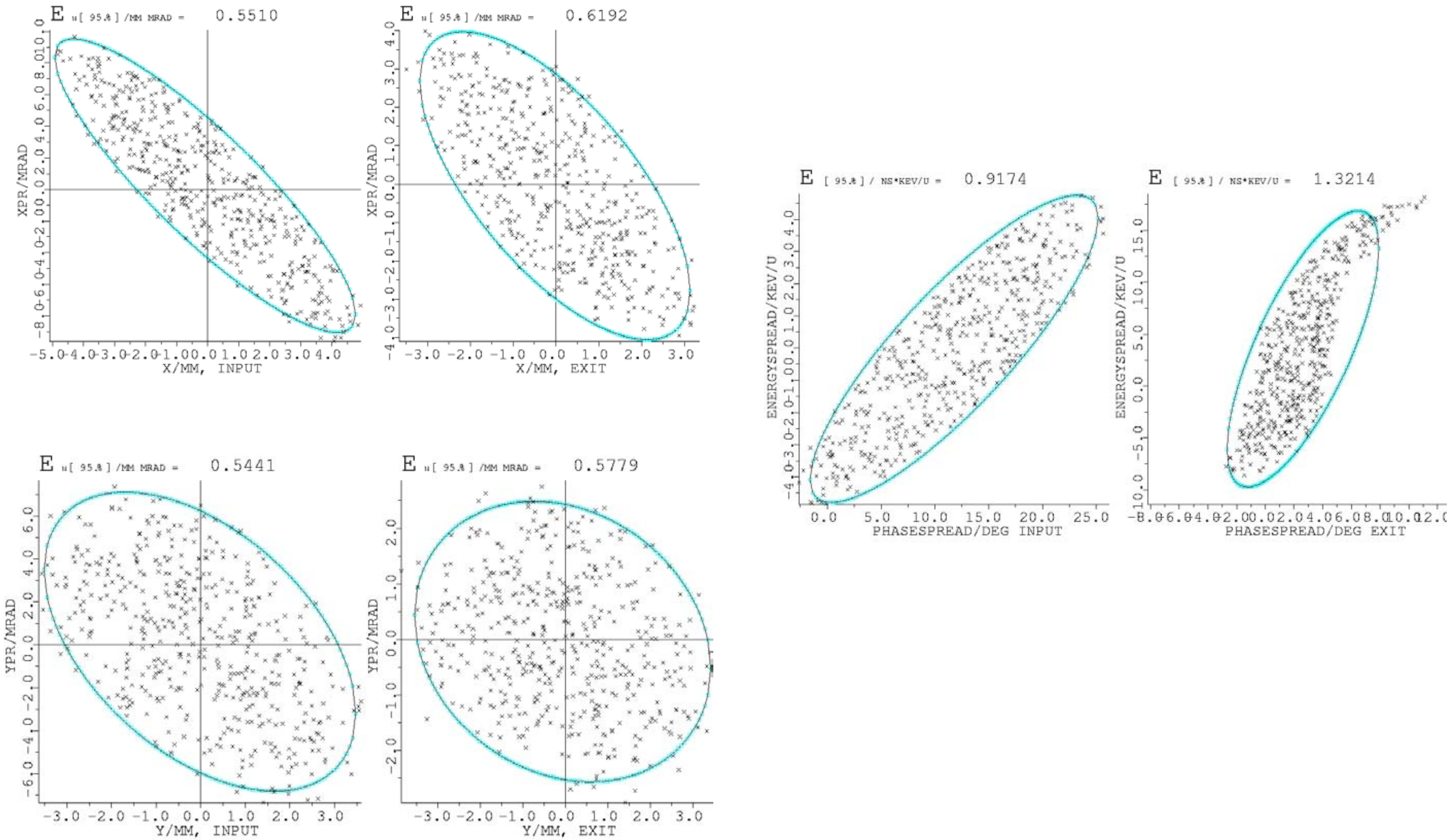


Fig. 3b) Top view on the middle part of the GSI-cavity.

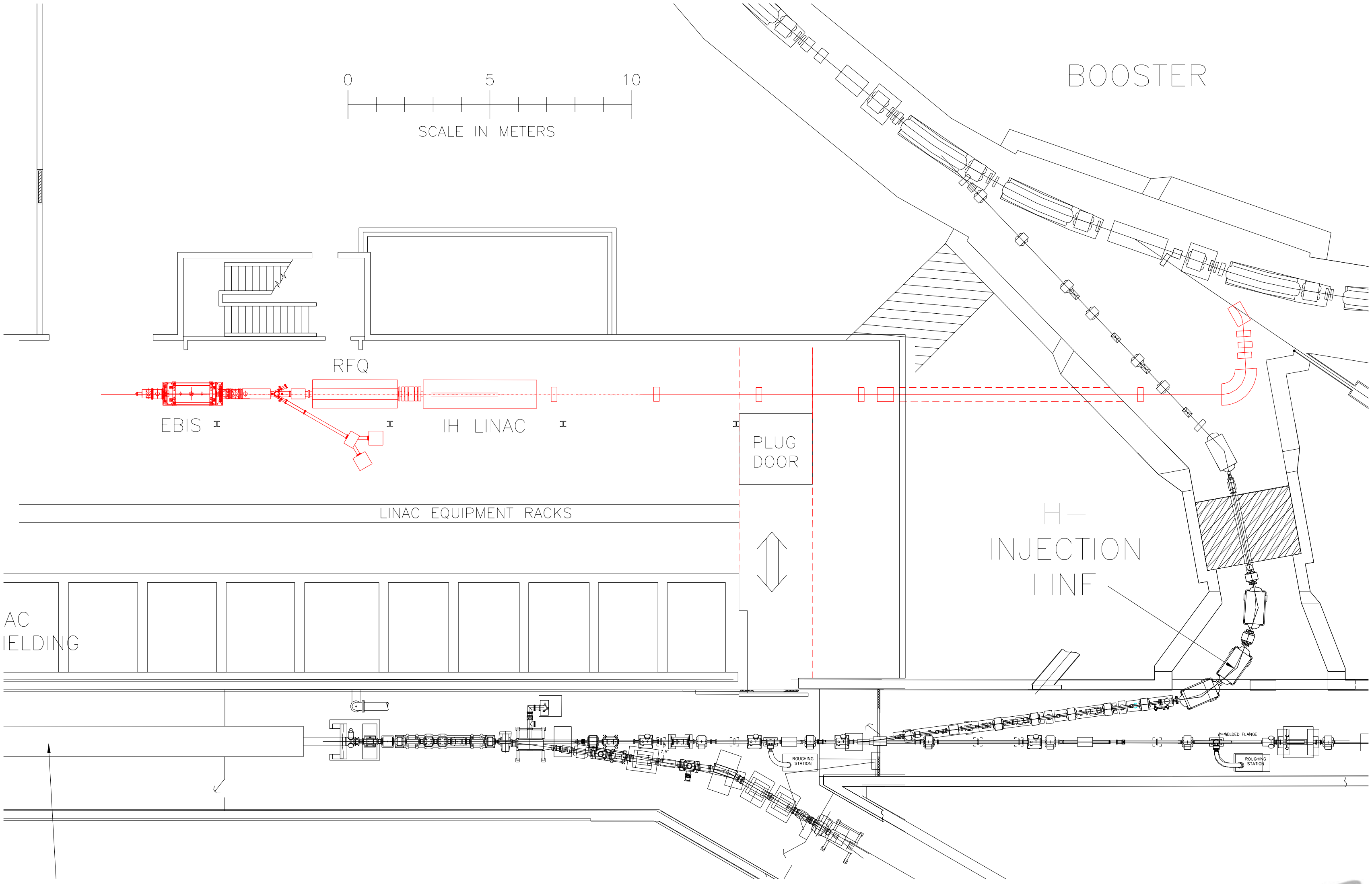
We have the IH linac optics codes, and have done a preliminary design



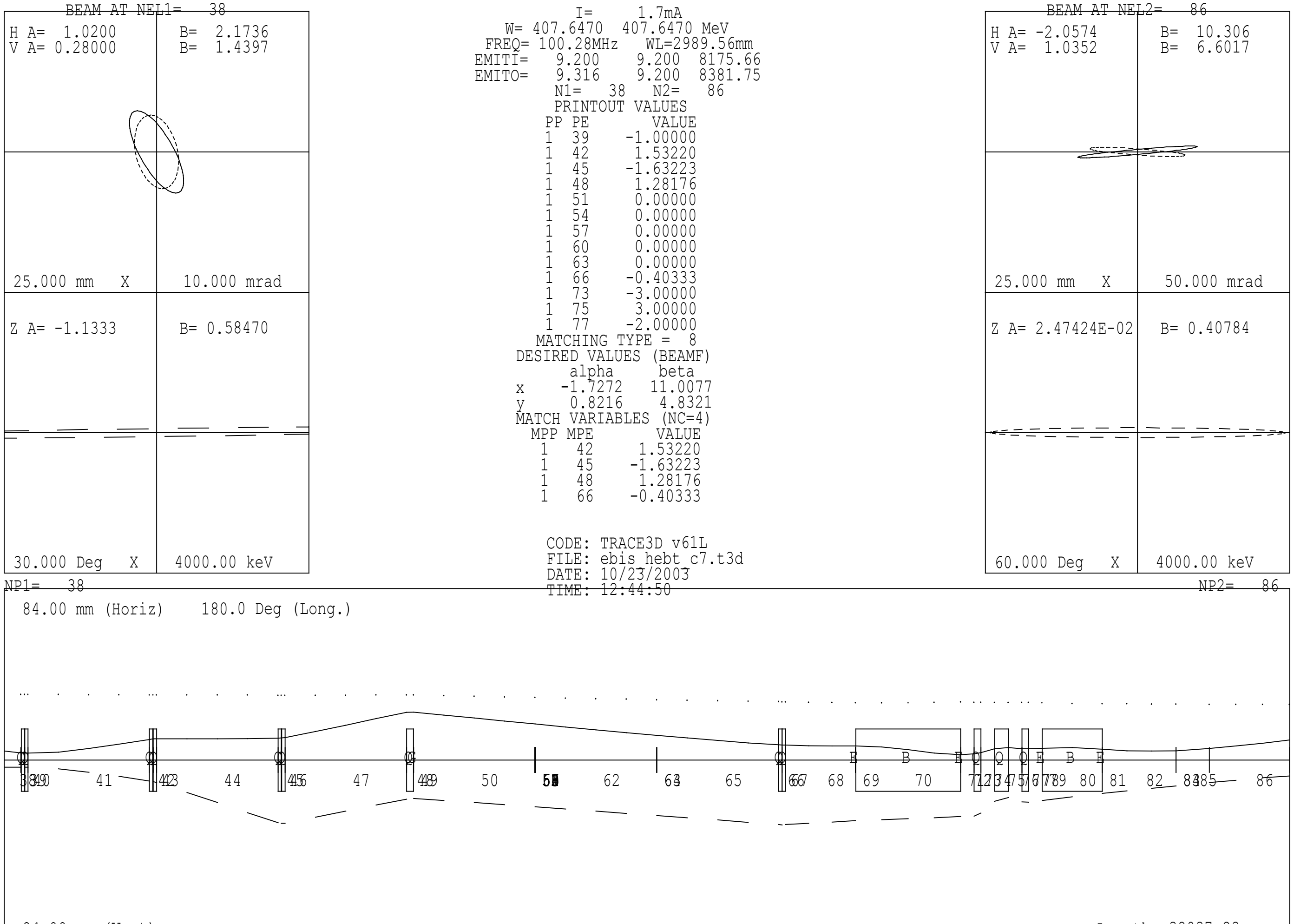
IH Linac Input and Output Emittances



Layout in the Linac Lower Equipment Bay



Optics of the Transport line to the Booster



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10/24/03

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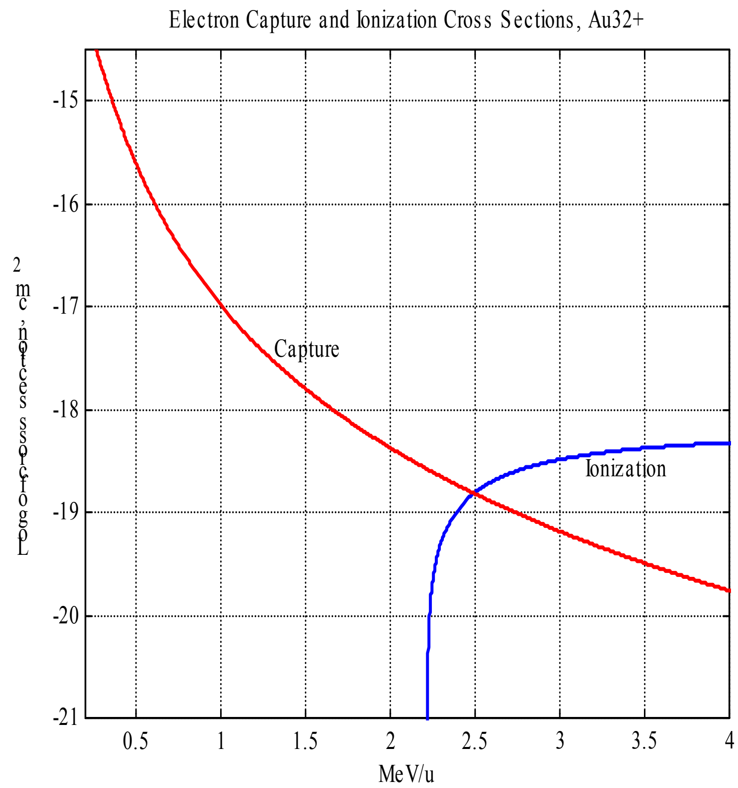
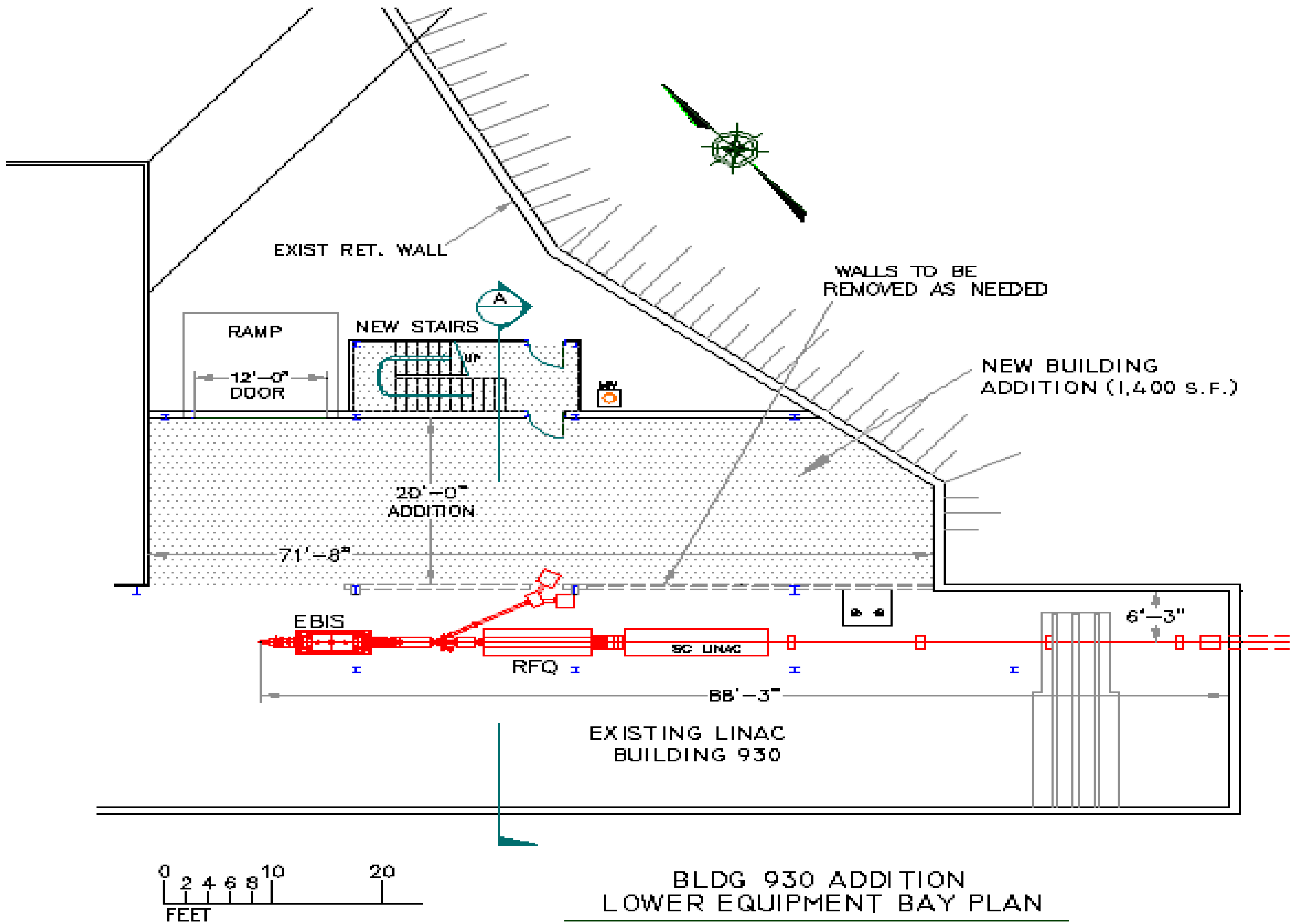
Booster Injection

With 1-4 turn injection, emittance in Booster will be smaller than from tandem (40 turns)

With dp/p = ±0.05%, requirements for longitudinal emittance in Booster are satisfied.

At 2 MeV/u, capture cross section reduced by factor of 40 relative to tandem.




EXIST RET. WALL
WALLS TO BE
REMOVED AS NEEDED
NEW BUILDING
ADDITION (1,400 S.F.)
RAMP
12'-0"
DOOR
NEW STAIRS
UP
A
20'-0"
ADDITION
71'-8"
EBIS
RFQ
SC LINAC
6'-3"
88'-3"
EXISTING LINAC
BUILDING 930
0
2
4
6
8
10
20
FEET
BLDG 930 ADDITION
LOWER EQUIPMENT BAY PLAN

CONCLUSION

The RHIC EBIS design will be very similar to the present EBTS operating at BNL.

No significant improvement in performance is required, other than the straightforward scaling of ion output with an increase in trap length.

Beyond this, changes to the EBTS design, which was a device built to demonstrate feasibility, will make the RHIC EBIS an "operational" device, i.e. simpler to maintain, and more reliable due to increased engineering margins on components.

A proposal has been submitted to DOE for EBIS/RFQ/Linac construction (possible start in FY'05 ?).